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SPACECRAFT HIGH-VOLTAGE POWER SUPPLY CONSTRUCTION

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16. Abstract

The design techniques, circuit components, fabrication techniques, and past experience which have been used in successful high-voltage power supplies for spacecraft flight systems are described. A discussion of the basic physics of electrical discharges in gases is included and a design rationale for the prevention of electrical discharges is provided. Also included are typical examples of proven spacecraft high-voltage power supplies with typical specifications for design, fabrication, and testing.

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PREFACE

Studies have shown that voltage breakdown is a recurring problem in high-voltage spacecraft systems and that about 75 percent of the breakdown problems are attributable to faulty design of the high-voltage power systems. The major reason for the recurrence of high-voltage power breakdown problems is the lack of documentation describing those special design and fabrication techniques which have yielded successful flight high-voltage power supply hardware.

The information contained in this document has been gathered from many sources in the aerospace industry and in the Government. It includes the fundamentals of voltage breakdown, specific information on materials, components, parts selection, processing, encapsulation and conformal coating, stresses on parts, outgassing, venting, and mechanical arrangement. Typical examples of successful high-voltage power supplies are included.

J. F. Sutton
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SPACECRAFT HIGH-VOLTAGE POWER SUPPLY CONSTRUCTION

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INTRODUCTION

Breakdowns associated with spacecraft high-voltage power supplies are a recurrent problem. Because three out of four breakdowns can be attributed to faulty design (Reference 1), a collection of design data parameters for high-voltage power supplies should prove useful to experimenters. This document includes design aids and listings of some material properties. Although this collection of data is not comprehensive, it is representative of the types of problems that are frequently encountered.

A brief description of breakdown fundamentals is presented to serve as a basis for the parameters and problems explored. Also presented are details of design experience associated with encapsulation techniques (a promising new encapsulation technique is briefly discussed) the depressurization and outgassing of unpotted power supplies; and problems experienced with individual electronic components.

In order for designers to benefit from past experience in equipment designed for use in the severe space environment, current design practices and several successful high-voltage power supplies are described. These incorporate several techniques for solving the breakdown problem and may aid in new designs.

The appendixes include three documents which provide examples of careful attention to detail given during the design, fabrication, and testing of power supplies. They are JPL Des. Req. DM505139 A, GSFC Specification 31187B "Helios A & B Missions Detector Bias Supplies and Low Voltage Power Supplies for Experiment," and "Specifications for Photomultiplier Tube Power Converter PS-13A," a GSFC internal specification (Trainor). Successful high-voltage power supplies have been produced and flown in NASA spacecraft using these design requirements and specifications.

It is hoped that the data and suggestions included here will prove helpful to new spacecraft experiment design groups. Suggestions, comments, and new data will be welcomed by the authors.

BREAKDOWN FUNDAMENTALS OF GASES

Changes in gas insulation properties resulting from electric field variations, pressurization and surface effect of electrodes, and solid dielectric failures are fundamental contributors to high-voltage breakdown. This section provides some basic theory and experimental results applicable to spacecraft high voltage systems.

GASES-THEORY

A gas progresses from an almost perfect insulator to a semiconductor and finally to a conductor, when a uniform electric field of increasing intensity is applied. This progression is illustrated in Figure 1. (For a detailed study of electrical breakdown in gases see Reference 2.)

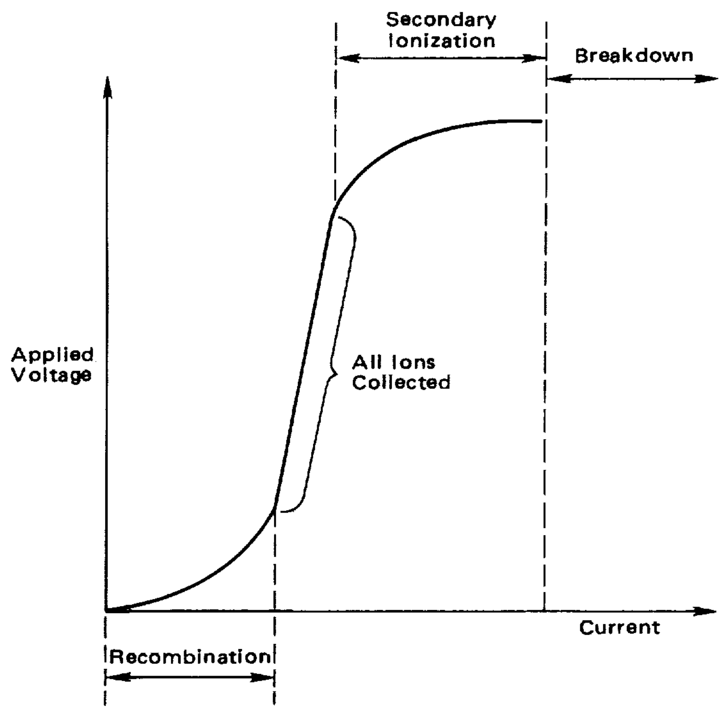


Figure 1. Voltage-Current Characteristic for a Gas in a Uniform Electric Field.

The first region of interest in Figure 1 is labeled Recombination. In this region, electrons released from a cathode by background radiation, for example, cosmic rays, tend to return to the cathode by back diffusion and because of the space charge field. At a higher applied field intensity, these effects are largely overcome so that essentially all of the ions and electrons are collected by the electrodes. In the Secondary Ionization region, N_0 initiating electrons each cause α ionizations per unit distance traveled in the field direction resulting in a rate of release of new electrons of

$$dN = N_0 \, \alpha dx$$

from which is derived the number of electrons that reach the anode at a distance d. That is,

$$N = N_0 e^{\alpha d}$$

The next region, Breakdown, exhibits a rapidly increasing current due to the production of additional electrons at the cathode. These electrons are generated principally by positive ion bombardment. The effect of this secondary emission due to positive ion bombardment may be understood by following the sequence of events illustrated in Figure 2. (This discussion follows that given in Reference 3.)

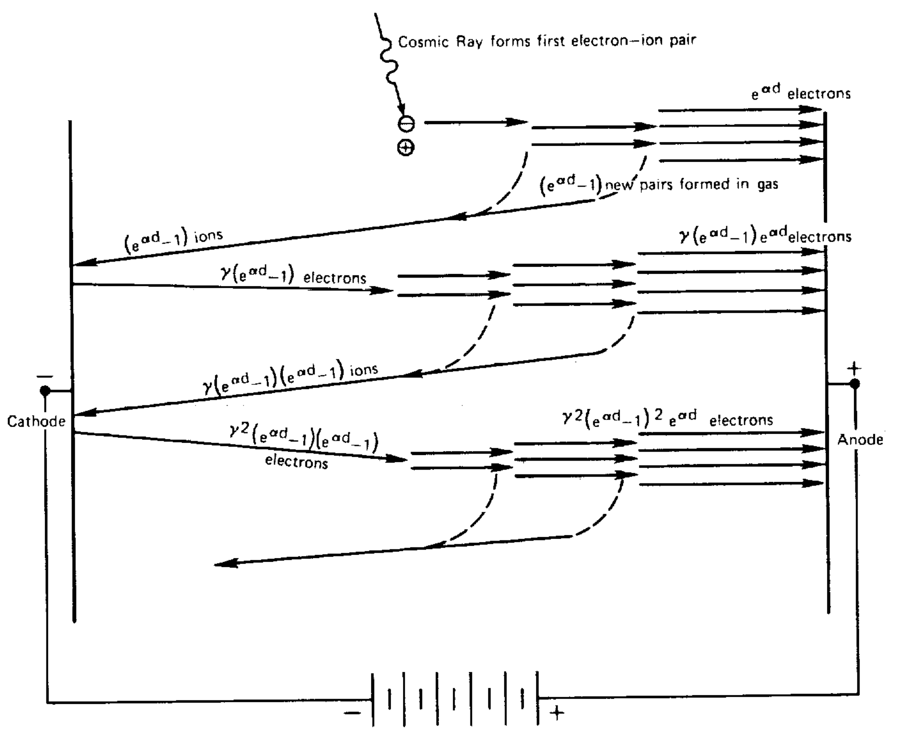


Figure 2. Derivation of Townsend's Breakdown Criterion.

A cosmic ray releases an electron which causes an avalanche resulting in $e^{\alpha d}$ electrons being collected by the anode; that is, $(e^{\alpha d}-1)$ new ions are formed in the gas and are collected at the cathode. A fractional number, γ, of electrons is released at the cathode by each of these ions and results in anode secondary emission of $\gamma (e^{\alpha d}-1)$ electrons. Each of these electrons causes an avalanche, so $\gamma (e^{\alpha d}-1) e^{\alpha d}$ new electrons travel to the anode. This process repeats so that N_0 initial cosmic-ray-produced ion-electron pairs cause a total number, N, of electrons to flow to the anode, where

$$
\begin{aligned}
N &= N_0 \left[e^{\alpha d} + \gamma (e^{\alpha d} - 1) e^{\alpha d} + \gamma^2 (e^{\alpha d} - 1)^2 e^{\alpha d} + \ldots\right] \\
&= N_0 e^{\alpha d} \left[1 + \gamma(e^{\alpha d} - 1) + \gamma^2 (e^{\alpha d} - 1)^2 + \ldots\right] \\
&\equiv N_0 e^{\alpha d} \frac{1}{\left[1 - \gamma (e^{\alpha d} - 1)\right]}
\end{aligned}
$$

N becomes infinite (Townsend sparking criterion) when the denominator is zero. If the number of ion pairs $(e^{\alpha d}-1)$ produced by one original ion is much greater than one, then $(e^{\alpha d}-1) \approx e^{\alpha d}$, and the breakdown condition becomes $\gamma e^{\alpha d}=1$. This criterion is subject to certain limiting factors as noted by von Engel (Reference 4).

GASES-EXPERIMENTAL RESULTS

The above theoretical treatment can be used as a basis for understanding electrical breakdown in gases. Experimentally, Paschen's Law for uniform fields is a useful design tool for avoiding breakdown. Basically, the average amount of kinetic energy an electron gains between collisions depends on the mean free path length, λ, (Figure 3) which is determined by the collision cross section and gas density. The kinetic energy gained between collisions in turn determines the cross section for ionization of a gas molecule. Thus, it is expected that the breakdown potential should be some complex function of density and electrode system geometry. This is indeed the case as illustrated by the Paschen curves of Figure 4 (Reference 5). At high pressures (that is, density), λ is small; therefore, electrons gain too little energy per path to produce ionization. At low pressures there are too few atoms to produce substantial numbers of ions. At pd values of ~1 torr-cm, a gas composition-dependent minimum of ~350 volts occurs. Assuming a 1-cm electrode separation as typical, one can readily see by referring to Figure 5 that sounding rocket or spacecraft instruments which must operate while passing through altitudes of 30 to 65 km are particularly prone to corona problems.

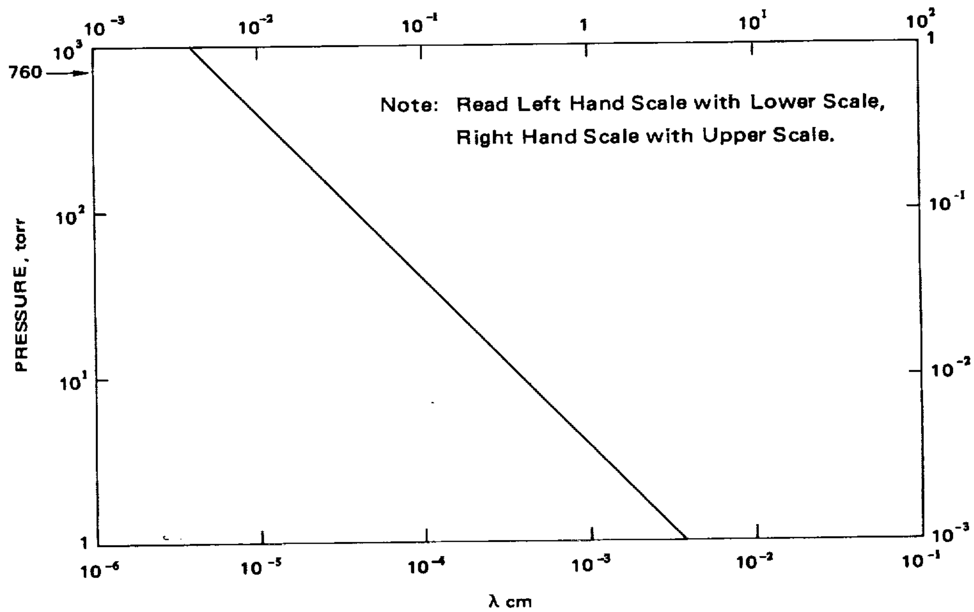


Figure 3. Electron Mean Free Path in Air vs. Pressure.

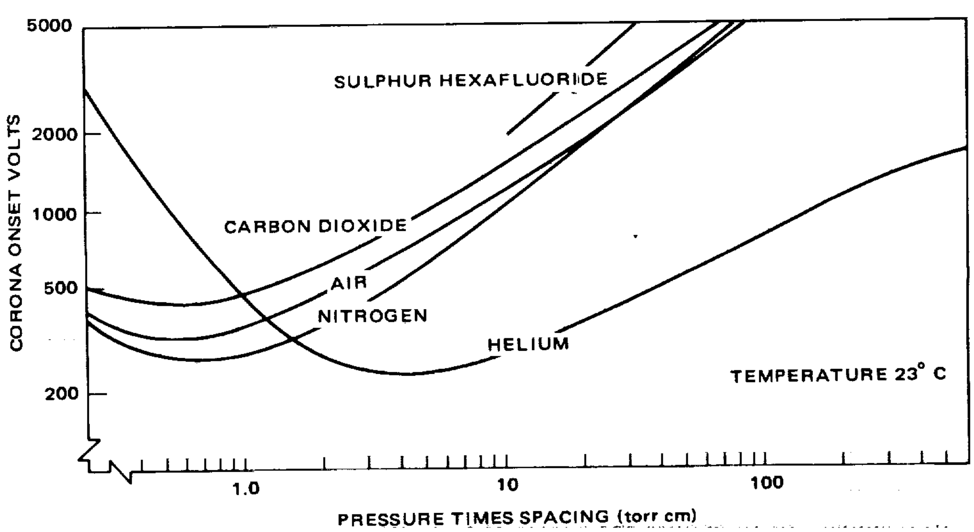


Figure 4. Direct Current Breakdown Voltage Between Parallel Plates for Several Gases.

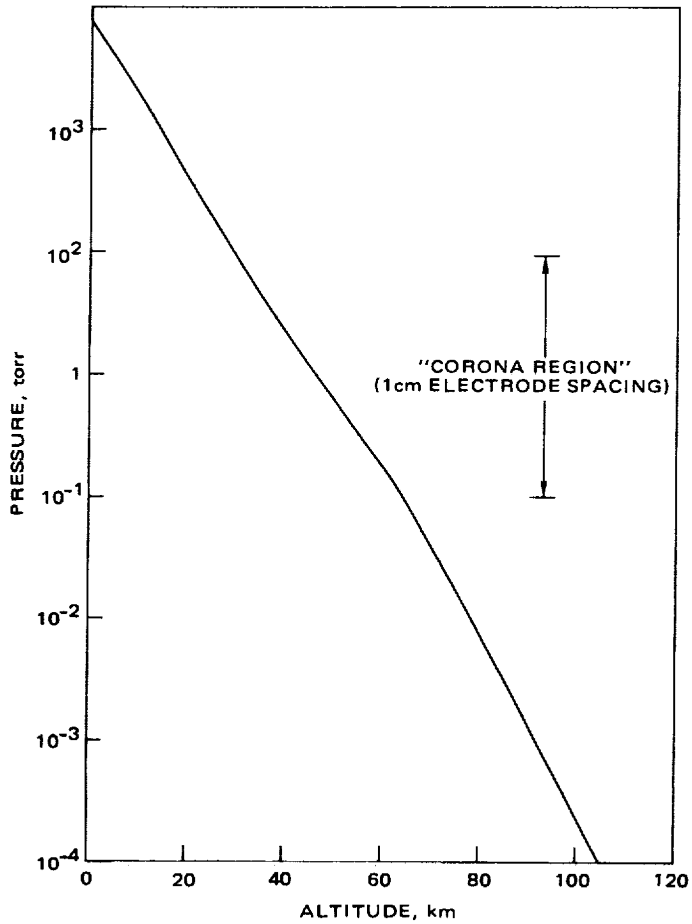


Figure 5. U.S. Standard Atmosphere, 1962, NASA, USAF, and USWB, 1962. (Reference 6)

In practice, one rarely deals with uniform fields. Nevertheless, Paschen-type curves such as those in Figures 6, 7, and 8 can be used to qualitatively predict the results of design perturbations.

Table 1 is a useful compilation of data that can be applied to estimate the maximum field which would be developed for any common electrode arrangement or to choose the better of two alternatives. Note, for example, that the hemisphere-in-a-plane configuration results in a lower maximum field than that of the sphere-and-plane configuration when $a \gg r$. Also, the maximum field produced between parallel wires is the same as that between wires crossing at right angles.

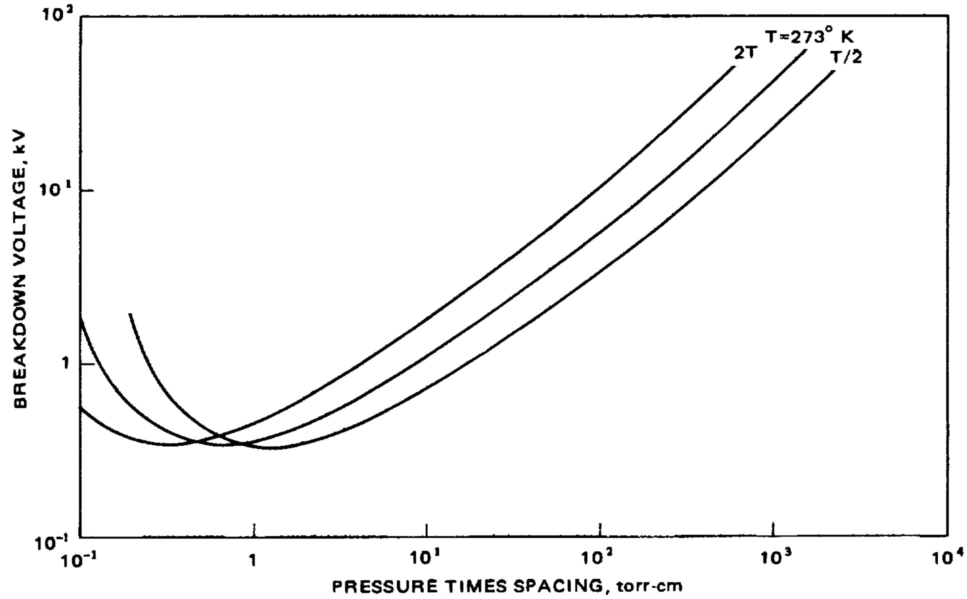


Figure 6. Effect of Temperature on Paschen Curve.

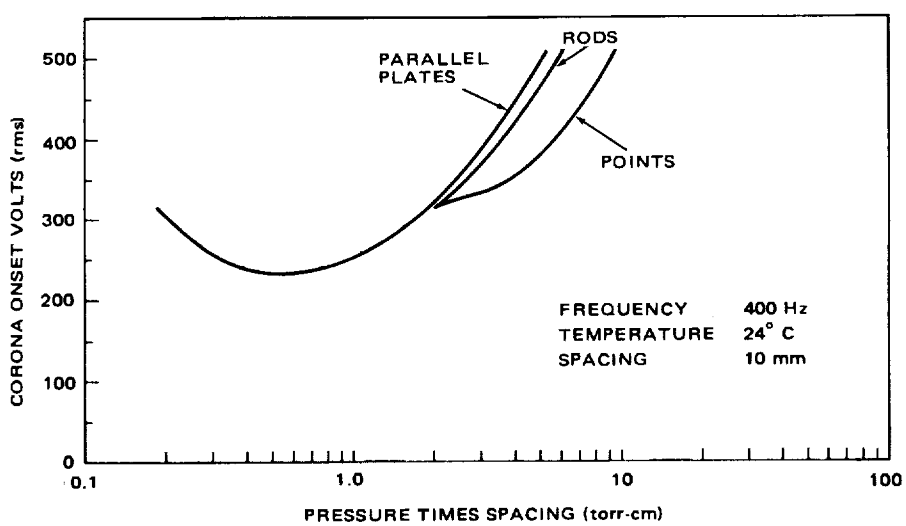


Figure 7. Effect of Electrode Geometry on Breakdown Characteristic in Air. (Reference 5)

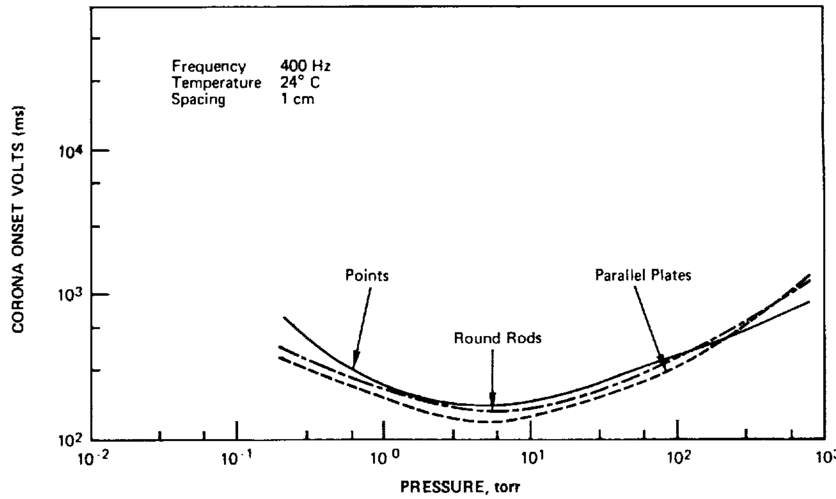


Figure 8. Effect of Electrode Geometry on Breakdown Characteristic in Helium. (Reference 5)

It is the gas density, not pressure, which is important when considering gas breakdown. The temperature variation, Figure 6, is found from the perfect gas law; that is,

$$\frac{p_1 V_1}{p_2 V_2} = \frac{n_1 R T_1}{n_2 R T_2}$$

If $p_1 = p_2$ and $V_1 = V_2$ then

$$\frac{n_1}{n_2} = \frac{T_2}{T_1}$$

Thus, in order to see the effect on a Paschen curve of doubling the temperature, the curve should be replotted with pressure values halved.

Further complications relate to the type and condition of the electrode surfaces. The type of material can significantly affect the breakdown potential (Table 2). This should be expected under high field conditions on the basis of variations in Townsend's second coefficient. Surface irregularities forming high field concentrations on sharp points can lead to field emission. The charging of insulating particles on electrode surfaces leading to high fields (Malter effect) and the transfer of particles from one electrode to the other (clumping), with resulting thermally-assisted electron emission, are other mechanisms that cause departure from ideal behavior. The curve of Figure 9, having a plateau at low pd values, is one example of such behavior under nonideal conditions.

Table 1
Maximum Field Strength E with a Potential Difference U Between the Electrodes, for Several Electrode Configurations (Reference 7)

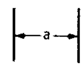
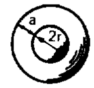
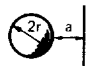
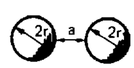
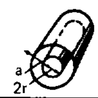
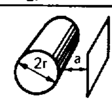
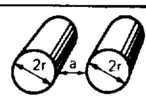
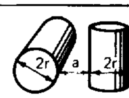
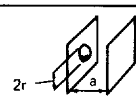
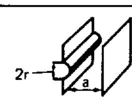
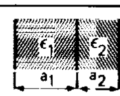
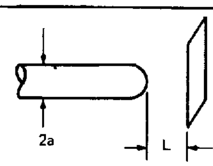
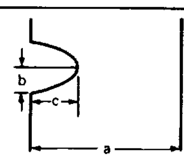
Configuration		Formula for E	Example
Two parallel plane plates		$\frac{U}{a}$	U = 100 kV, a = 2 cm, E = 50 kV/cm.
Two concentric spheres		$\frac{U}{a} \cdot \frac{r+a}{r}$	U = 150 kV, r = 3 cm, a = 2 cm, E = 125 kV/cm.
Sphere and plane plate		$0.9\ \frac{U}{a} \cdot \frac{r+a}{r}$	U = 200 kV, r = 5 cm, a = 8 cm, E = 58.5 kV/cm.
Two spheres at a distance a from each other		$0.9\ \frac{U}{a} \cdot \frac{r + a/2}{r}$	U = 200 kV, r = 5 cm, a = 12 cm, E = 33 kV/cm.
Two coaxial cylinders		$\frac{U}{2.3\, r\, \lg \frac{r+a}{r}}$	U = 100 kV, r = 5 cm, a = 7 cm, E = 22.9 kV/cm.
Cylinder parallel to plane plate		$0.9 \frac{U}{2.3\, r\, \lg \frac{r+a}{r}}$	U = 200 kV, r = 5 cm, a = 10 cm, E = 32.8 kV/cm.
Two parallel cylinders		$0.9 \frac{U/2}{2.3\, r\, \lg \frac{r+a/2}{r}}$	U = 150 kV, r = 6 cm, a = 20 cm, E = 11.5 kV/cm,
Two perpendicular cylinders		$0.9 \frac{U/2}{2.3\, r\, \lg \frac{r+a/2}{r}}$	U = 200 kV, r = 10 cm, a = 10 cm, E = 22.2 kV/cm.
Hemisphere on one of two parallel plane plates		$\frac{3U}{a}$; $(a \gg r)$	U = 100 kV, a = 10 cm, E = 30 kV/cm.
Semicylinder on one of two parallel plane plates		$\frac{2U}{a}$; $(a \gg r)$	U = 200 kV, a = 12 cm, E = 33.3 kV/cm.
Two dielectrics between plane plates $(a_1 > a_2)$		$\frac{U\epsilon_1}{a_1\epsilon_2 + a_2\epsilon_1}$	U=200kV, ϵ_1=2, ϵ_2=4, a_1=6 cm, a_2=5cm, E = 11.8 kV/cm.
Point and Plane $\frac{L}{a}$ =160		$\frac{0.605\ U}{a}$	U = 1kV, L=160 cm, a=1cm E = 605 volts/cm. Compare parallel plate capacitor with E = 6.25 volts/cm
Ellipsoidal Boss on one of two Parallel Planes II		$\frac{U}{a} \times \beta$ $\beta \approx [n(\coth^{-1} n - 1/n)(n^2 - 1)]^{-1}$ where $n = c\,(c^2 - b^2)^{½}$	$\frac{c}{b} = 10, \beta \approx 50$

Table 2
Breakdown Voltages for Several Electrode Materials
(Reference 9)

(1-mm gap after conditioning with glow discharge)

Material	Breakdown Voltage (kV)
Steel	122
Stainless Steel	120
Nickel	96
Monel Metal	60
Aluminum	41
Copper	37

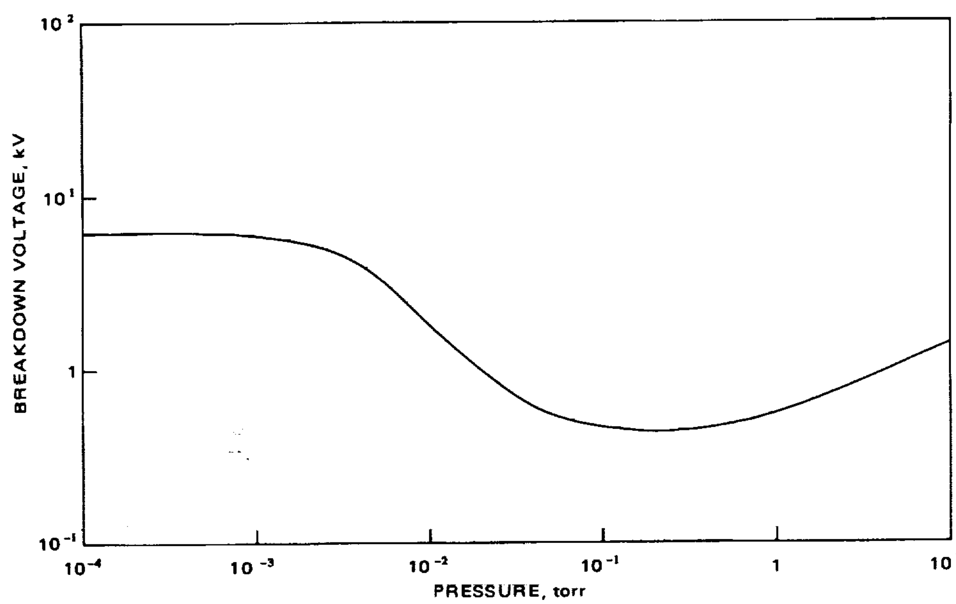


Figure 9. Breakdown Under Nonideal Conditions Showing Plateau at Low Pressures (after G. Biddison, private communication, 1968).

The importance of minute surface irregularities should not be overlooked. The microscopic field enhancement factor, β_1, due to an ellipsoidal boss on one plate of an ideal parallel plate capacitor is plotted in Figure 10. Total field enhancement is the product of β_1 times an electrode geometry factor, β_2, which can range from 1 to 10 (Reference 8). Such enormous field enhancement factors ($\beta_1\beta_2$ products of ~10^2 - ~10^5) can easily lead to field emission with subsequent voltage breakdown. They account for some of the wide variations in breakdown voltages reported in the literature.

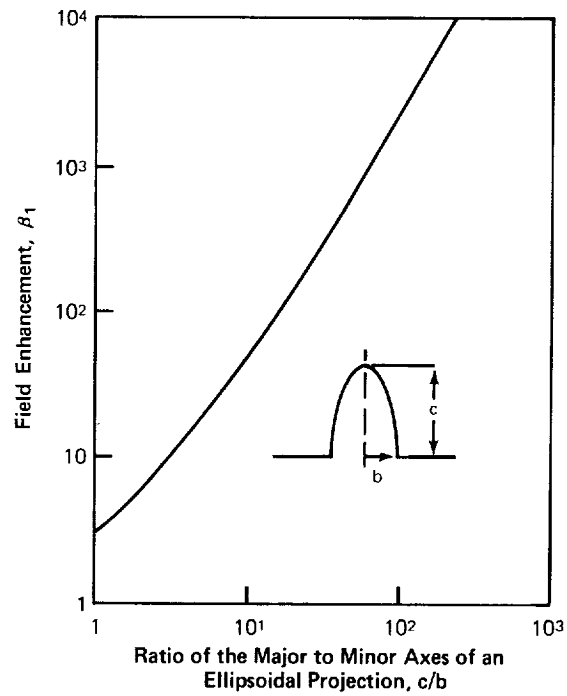


Figure 10. Microscopic Field Enhancement Factor β_1 as a Function of Geometry for an Ellipsoidal Boss on an Otherwise Flat Infinite Plane.

At very low pressures (vacuum insulation) and voltages below ~20 kV, breakdown is initiated by electron emission from the cathode. Above ~20 kV, processes that depend on the total voltage become more important than field emission (Reference 9). These processes include electron and ion bombardment of the electrode surfaces accompanied by emission of positive ions, electrons, and photons. The effect of such charged particles and photon interchange between the electrodes is to make required electrode spacings increase rapidly with applied voltage (Figure 11). It must also be remembered that surface materials are often not the same as the base materials and can radically affect breakdown voltage. Aluminum oxide, for example, exhibits a much higher secondary electron yield than that of aluminum.

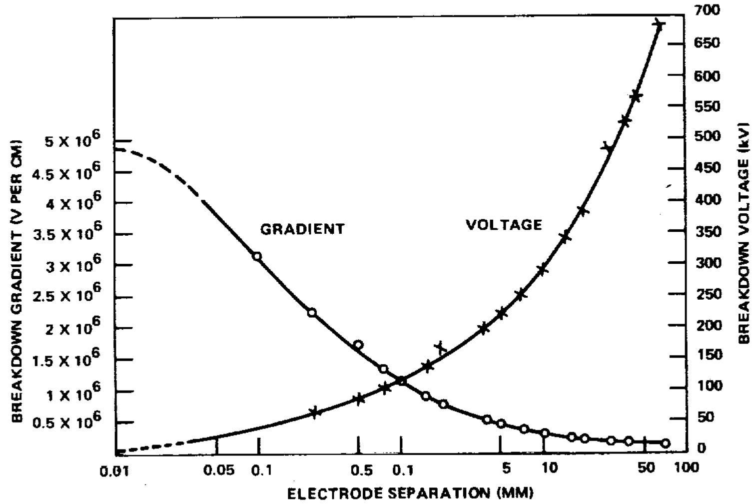


Figure 11. Breakdown Voltage and Breakdown Voltage Gradient Between a Steel Sphere, of 1-in. Diameter, and a Steel Disc, of 2-in. Diameter, in Vacuum. (Reference 10)

Surface Effects

As shown in Figure 12, the addition of dielectric surfaces between two electrodes can reduce breakdown voltage by a factor of 2 or more at high pressures, whereas there is very little effect at low pressures (Reference 11). Such behavior is probably due to adsorbed water vapor as suggested by the study by Sprengling and Ponemone (Reference 12). They found that volume resistivity of epoxy glass circuit laminates along the warp and woof directions was reduced several decades by exposure to high humidity. Sprengling (Reference 13) has found a long term irreversible susceptibility to reduction in surface resistivity due most likely to oxidation caused by the adsorbed water. Silicones and fluorocarbons were found to be the most resistant to this type of degradation.

A major problem with surface breakdown is the development of conductive paths or tracks which can lead to permanent short circuiting of the high voltage. Table 3 is a listing of the arc resistances and other characteristics of some materials commonly used in fabrication of electronic devices.

PRESSURIZATION AND ELECTRONEGATIVE GAGES

Normally, high-voltage power supplies employed on spacecraft take advantage of the high values of breakdown voltage available at low pressures. It is also possible to take advantage of the high V_b values at the other end of the Paschen curve by pressurization. For example, as shown in Figure 13, it is possible to double V_b by pressurization to ~350 kN/m^2 (~50 psig) with air or CO_2 or N_2. A better approach is the use of an electronegative gas,

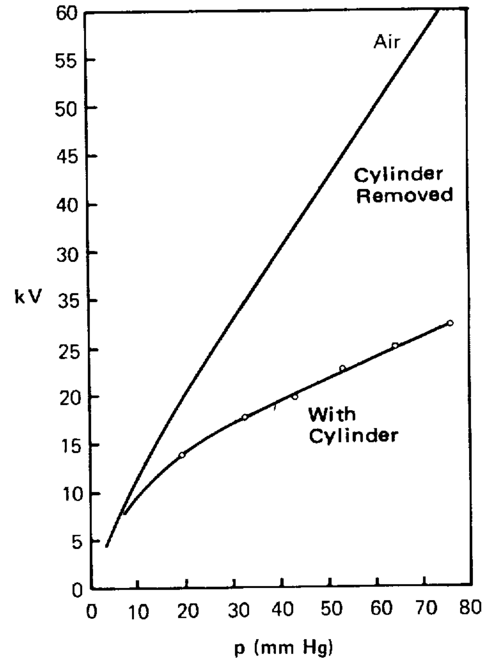


Figure 12. Breakdown Voltage for Sparkover Across Surface of a 2-cm-long Glass Cylinder in Air. Curve Labelled "Air" Gives Breakdown Voltage of the Gap with the Glass Cylinder Absent. (Reference 11)

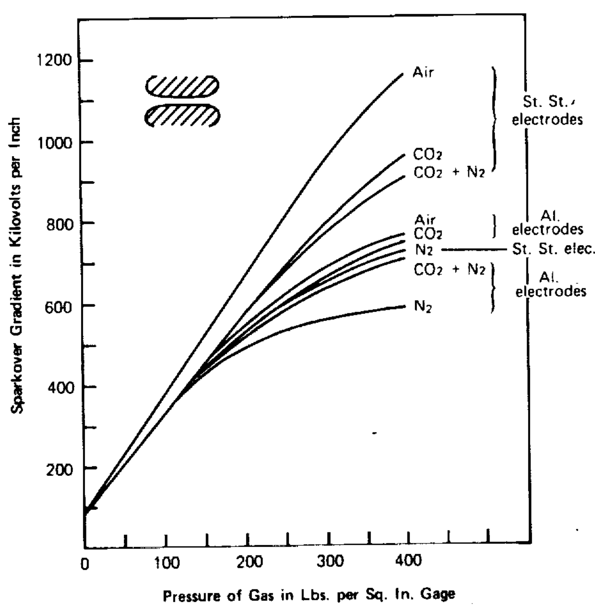


Figure 13. Comparative Insulating Strength of Several Gases at High Pressures for Uniform Fields Between S.S. and Aluminum Electrodes. (Reference 10)

Table 3
Dielectric Strength and Arc Resistance for Selected Insulation Materials Suitable for Molding, Extrusion or Casting*

Material	Arc Resistance (seconds)	Dielectric Strength (volts per mil)	Volume Resistivity Ω-cm	Dielectric Constant
Acetal resin copolymer	240	500–2100	10^{14}	
Acetal resin homepolymer	129–240 (burns)	500–1210	$1-6\times10^{14}$	
Acrylic resins	no tracks	400–500	2×10^{16}	
Acylonitrile Butadiene–Styrene	71–82	310–460	10^{16}	
Alkyd molding compound	180+	375	10^{14}	5.8–6.2
Cellulose acetate	50–310	230–365	$10^{10}-10^{14}$	3.5–4.0
Cellulose acetate butyrate	unknown	250–400	$10^{10}-10^{15}$	3.6–6.4
Chlorinated Polyether	unknown	400	10^{15}	
Ethyl cellulose	60–80	800	$10^{12}-10^{15}$	
Delrin	125–190	400	$10^{15}-10^{16}$	2.7–3.7
Deallyl phthalates	105–140	350–400	$3.9\times10^{12}-1.8\times10^{16}$	6.2
Expoxies	45–300	300–550	$10^{12}-10^{17}$	3.3–5.5
Ethylene	unknown	525–550	$10^{8}-10^{9}$	
Fluorinated ethylene and propylene (copolymer)	>300	500–600	$>2\times10^{18}$	
Kel–F	>360	~500–1000	$2.5-4\times10^{16}$	
Melamine with glass Fibers	180	170	10^{11}	
Mica–glass bonded	240–300 +	350–400	$10^{12}-10^{17}$	
Neoprene	unknown	150–600	10^{11}	
Nylons	130–140	342–470	$1.5\times10^{11}-4\times10^{14}$	3.9–7.6
Nylons with glass fibers	92–148	400–580	$3.0-5.5\times10^{14}$	
Phenolic molding compound	tracks	300–400	$10^{11}-10^{17}$	
Phenolic molding compound with glass fibers	0.4 to 150	100–450		
Oxide resins	unknown	500–550	10^{17}	
Phenylene oxide resins with glass fibers	70–120	1020	10^{17}	
Polycarbonate	120	400	$2-1\times10^{16}$	3.1
Polychlor otrifluoroethylene	>360	530	1.2×10^{18}	
Polyethylene, irradiated	unknown	2500	$>10^{15}$	2.25–3.2
Polyimides	230	560	$10^{16}-10^{17}$	
H film (5 mil)	183 tracks	3600	10^{18}	
Polypropylene	unknown	750–800	$>10^{16}$	
Polypropylene with glass fibers	73–77	317–475	1.7×10^{16}	
Polystyrene (heat resistant)	60–135	400–600	$10^{16}-10^{17}$	
Polysulfones	122	425	10^{16}	
Polytetrfluoroethylene	>300	480	$>10^{18}$	
Polyvinyl chloride (Flexible)	unknown	250–800	$10^{11}-10^{14}$	12.0
Polyvinyl chloride (Rigid)	60 – 80	425–1300	$>10^{16}$	2.4
Polyvinylidene fluoride	>50	260–1280	2×10^{14}	
Silicone, Mineral filled	230	390	5×10^{13}	4.8
Styrenes with glass fibers	28 – 41	354–424	$3.2-3.7\times10^{16}$	
Urethanes	unknown	6.7-7.5 (60 Hz.)	2×10^{11}	
Viton, fluoroelastomer	unknown	500	2×10^{13}	
Vespel	230	400	$10^{16}-1^{17}$	3.0–3.5

*These values are obtained under standard test conditions and may not be obtained in engineering applications.

especially SF_6. Molecules of SF_6 readily capture electrons and form heavy negative ions with much lower mobility than the electrons. In addition, SF_6 is stable below 423°K (150°C), is nontoxic, and does not burn. Figures 14 and 15 illustrate the significant improvement in V_b obtainable through the use of SF_6 (Reference 14). A 100-kV power supply, described later in this report, has been successfully designed using pressurization with SF_6.

SOLID DIELECTRIC FAILURES

Solid dielectric failures are generally of two types: mechanical and chemical. Mechanical breakdown is failure due to mechanical overstress of the material by electrically produced physical forces. This failure mode occurs relatively infrequently.

Chemical breakdowns, which occur frequently, result from chemical changes and erosion of the dielectric material due to corona in voids or at external surfaces. Another factor which aids in the degradation of the electrical properties of dielectrics is heat produced by flow of leakage currents.

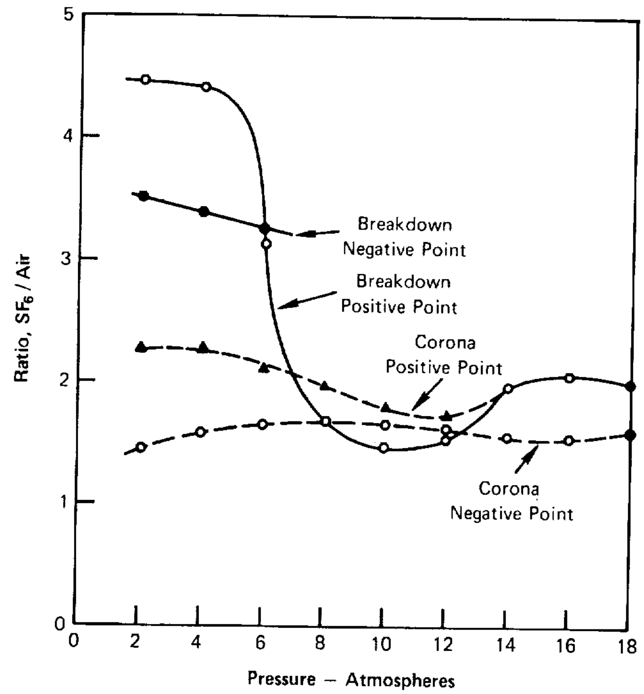


Figure 14. Ratio of Corona and Breakdown Voltage for Air and SF_6 as a Function of Testing Conditions in Nonuniform Fields. (Reference 14)

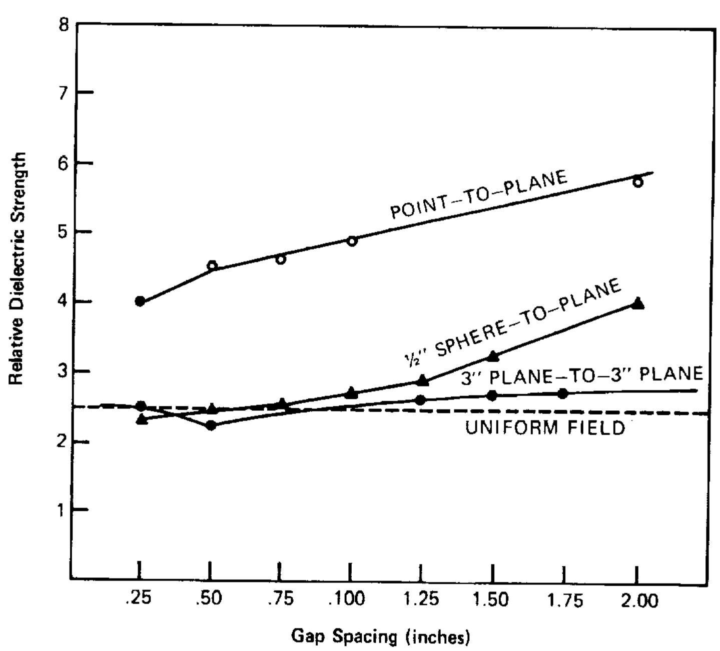


Figure 15. 60-Hz Relative Strength of SF_6 to Dry Air as a Function of Configuration and Spacing of Electrodes. Gases at 25°C and Atmospheric Pressure. (Reference 14)

Inhomogeneity of leakage resistance within the body of the dielectric coupled with poor heat conductivity can produce high temperatures with attendant chemical changes. These changes can cause a decrease of resistivity by several decades (Figure 16) of a portion of the material. The thickness of the dielectric is therefore effectively reduced and can lead to complete failure. This is the probable cause of the thickness effect–the variation of material dielectric strength with thickness in which the corona threshold voltage increases with dielectric thickness as expected (Figure 17), but the dielectric strength drops markedly (Figure 18).

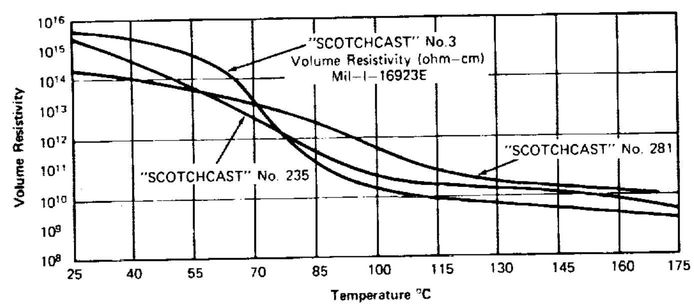


Figure 16. Volume Resistivity vs. Temperature for Three Encapsulant Materials.

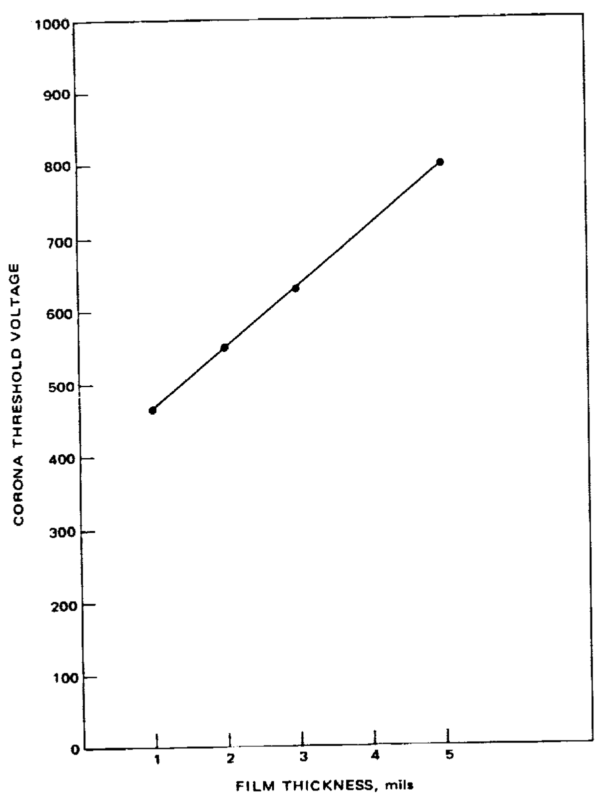


Figure 17. Dupont Kapton H-Film Corona Threshold Voltage vs. Film Thickness.

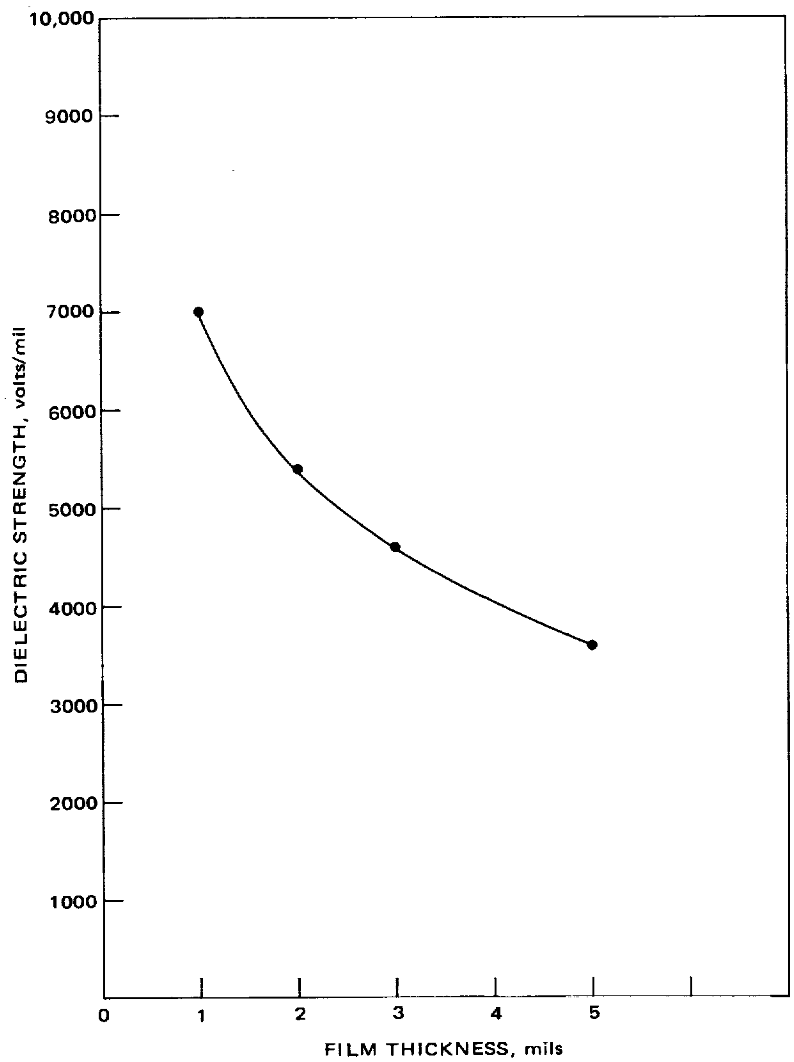


Figure 18. Dupont Kapton H-Film Dielectric Strength vs. Film Thickness.

DESIGN EXPERIENCE

Based on past experience, this section presents basic design information regarding individual components and processes. These include encapsulation techniques, selection of material and salient characteristics, voltage breakdown with regard to circuit boards, depressurization and outgassing of unpotted power supplies, and design information regarding problems with individual electronic components.

ENCAPSULATION

One method of preventing a gas discharge-voltage breakdown is to exclude gases from the high-voltage areas. This can be accomplished by encapsulating the high-voltage circuitry. Encapsulation provides the system with mechanical protection from external damage, structural support for the components against shock and vibration, and protects the high-voltage system from gas discharge damage.

Encapsulation of a high-voltage system is predetermined by the environmental conditions under which the system is expected to function successfully. The decision to encapsulate should be made during the initial design concept phase and incorporated in the subsequent hardware design. In this manner, a total system approach to the design can be taken, yielding a power supply with minimum problems that can arise from encapsulation or potting. This will permit the optimum choice of components, parts, materials, mechanical arrangements, manufacturing techniques, and the methods of functional and environmental testing.

Selection of Encapsulant

There are three general classes of encapsulants, potting materials or conformal coating materials, which are generally acceptable for spacecraft use: (1) epoxies, (2) silicones, and (3) polyurethanes. The main characteristic of selected members of these three polymer types is their low outgassing behavior, which reduces the problems of spacecraft contamination and internal spacecraft pressures conducive to electrical discharge. A list of specific polymers acceptable for flight use is given in GSFC Report, TM X-65679 and NASA TN D-7362. Other polymer characteristics that should be considered are dielectric strength, dielectric constant, resistivity, arc resistance or tracking, viscosity during the pouring period, pot life, shelf life, ease of handling during preparation and pouring, chemical activity with the parts to be encapsulated, need for primers on parts to be encapsulated, adhesion to parts, temperatures generated during the polymerization of the encapsulant, thermal coefficient of expansion of the polymer, and shrinkage during polymer cure. The use of flight-acceptable encapsulants is not without some hazards. A knowledge of what they are and how to avoid these hazards will greatly improve the probability of a successful and functional high-voltage system.

A major problem in encapsulation is the occurrence of voids in the encapsulant. This is particularly serious if voids occur in the neighborhood of large voltage gradients because an electrical breakdown in the void can be expected. This problem can be minimized by using care in the selection of an encapsulant and the encapsulation processing techniques. Dissolved gases should be removed from the encapsulant materials (resin and catylist), and gases should be prevented from becoming entrained in the encapsulant during the mixing and pouring stages. The technique for achieving these conditions is vacuum degassing of the encapsulant materials before mixing, then mixing and pouring in vacuum. To further ease the void problem, use an encapsulant which has a low viscosity in which entrained gas bubbles can easily rise and can be quickly removed from the fluid. It will also permit easy penetration of all the spaces between the circuit parts being encapsulated and help prevent void formation within the embedment. The mechanical arrangement and spacing of components also should be designed to prevent void formation and gas traps: for example, provide increased spacing between components when a more viscous encapsulant is to be used, and provide holes in circuit boards or other large surfaces to improve the distribution of the encapsulant around the surfaces and throughout the embedment assembly.

Another encapsulation problem is the mechanical stresses developed between the encapsulant and the embedded parts due to elevated temperatures, temperature differences, and encapsulant shrinkage. These stresses can be sufficiently severe to cause mechanical failure of the embedded circuit elements (breakage of leads, welded and soldered joints and electronic components under tension, compression or shear arising from a high shrinkage rate of the encapsulant or from a difference in thermal coefficient of expansion between the electronic part and the encapsulant).

This problem can be satisfactorily solved by choosing an encapsulating material whose physical, mechanical, and thermal characteristics are compatible with the components to be embedded. These properties can be modified by the addition of fillers to the encapsulant. In general, the fillers will decrease these values of thermal conductivity, coefficient of expansion (see Figure 19), mold shrinkage, exotherm temperature rise and mechanical strength, and increase the values of viscosity (see Figure 20) and dielectric constant. The curing rate of an exothermic polymerization reaction can be controlled during encapsulation to prevent the development of excessive temperatures and the accompanying thermal stresses. The encapsulated package should be designed such that heat dissipates as quickly as possible. A conformal coating of an elastomer also can help reduce the shear and

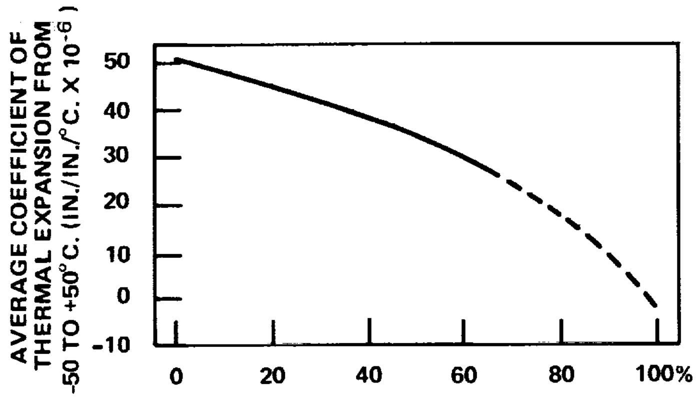


Figure 19. Coefficient of Thermal Expansion of Shell EPON 828 Castings with Silica Filler.

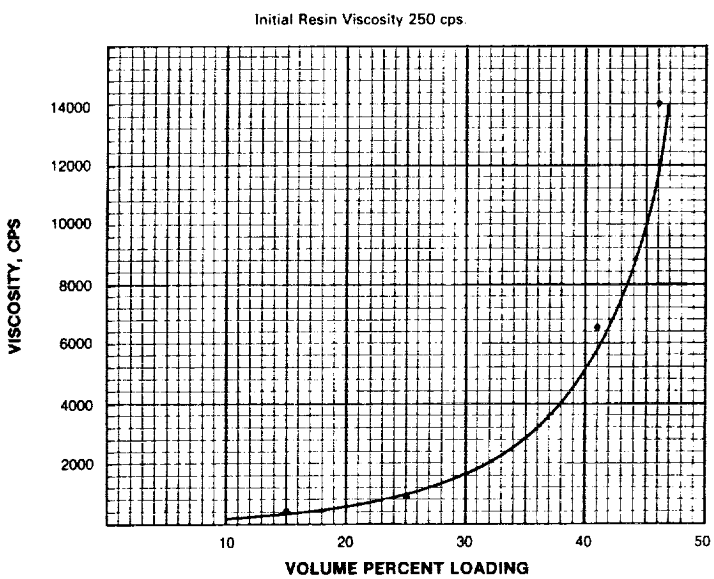


Figure 20. Effect on a Polyester Resin Viscosity Due to Filling with Glass Bubbles (3M Co.).

tensile stresses when a rigid encapsulation is desired. Some typical low outgassing conformal coatings are:

- Dow Corning 93-500, Polydimethyl Siloxane,
- Thiokol Solithane 113-300, Polyester type polyurethane,
- Hughson Chemical Chem Glaze Z 004, and
- Shell Epon 828/General Mills Versamide in a 50:50 to 70:30 ratio mix.

Assurance of a good bond between encapsulant and circuit parts is a requirement for a successful high-voltage encapsulation. This is dependent upon the chemical nature of the surfaces to be coated and the potting compound. Foreknowledge of the coating materials and the processing fluids to which the part has been exposed during manufacture and test will be very helpful in selecting the methods and materials for a successful encapsulation. It will determine the need for such surface preparations as chemical etching; mechanical abrasion (sand blasting or other surface scoring techniques); priming, when and as recommended by the encapsulant manufacturer; conformal coating; and cleaning. Cleanliness of surfaces to be coated is mandatory—no fingerprints, oils, or moisture should remain on the surfaces. Materials which are difficult to bond should be avoided. Teflon, in particular, should not be used in any potted system even though it can be surface treated. A typical cleaning fluid is a 1:1 solution of toluene and acetone of Certified Grade purity or better.

Epoxies

In addition to the low outgassing, low vapor pressure characteristics of epoxies, there are other properties which make them suitable as potting materials for spacecraft use. These include excellent electrical properties (dielectric constant = 3.0 to 5.0; dielectric strength = 400 to 600 volts/mil; volume resistivity = 10^{12} to 10^{16} ohm-cm; arc resistance = 50 to 180 s); good structural properties; low water absorption (0.17 - 0.50%); good adhesion to metals; and low mold shrinkage (0.007-0.009 in./in.). These properties are affected by the treatment and processing techniques. Volume resistivity, temperature coefficient of resistivity, dissipation factor, dielectric constant, heat conductivity, temperature coefficient of expansion, and viscosity are changed by the quantity and chemical nature of the hardening agents, fillers, plasticizers, and curing temperatures. Thermal conductivity of unfilled epoxies range from 4 to 5×10^{-4} cal/cm^2/s/cm/°C. Thermal coefficients of expansion for epoxies range from 40 to 100×10^{-6}/°C. The addition of suitable mineral fillers can reduce these coefficients to values more closely matching the temperature coefficients of the encapsulated parts thereby minimizing thermally induced stresses on these parts. Fillers also increase heat conductivity, decrease exotherm temperature rise, increase resin viscosity in amounts greater than 20% by weight, and reduce mold shrinkage.

The epoxies may be divided into two general classes: (1) those which are hardened at high temperatures by anhydride hardeners and (2) those which are hardened at about room temperatures by amine or amide hardeners. A comparison of the two classes shows that the anhydride hardened epoxies generally have better electrical properties (lower dissipation factors, higher volume resistivity (see Figure 21), electrical stability at elevated temperatures), higher heat distortion temperature, longer pot life and lower viscosity

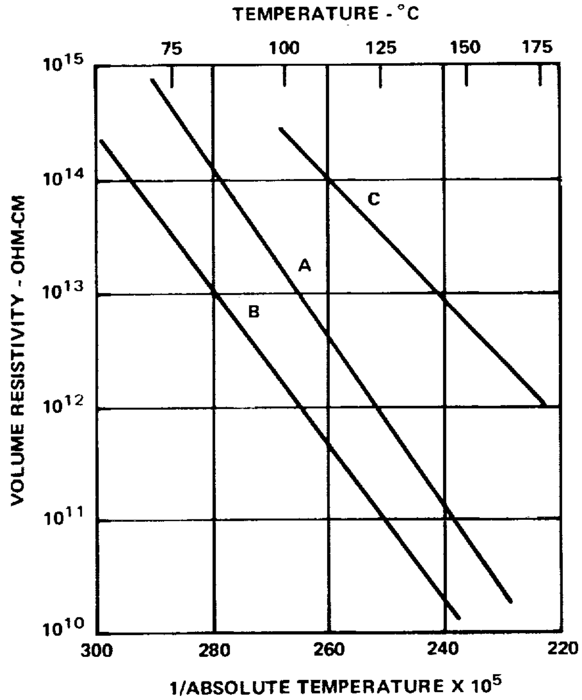


Figure 21. The Temperature-Resistivity Relation in Epoxy Resin as Affected by the Use of Different Hardening Agents. (Reference 15)

(easier to degas). The anhydride cured epoxy, however, does require an elevated cure temperature (100°C to 200°C) which will be injurious to circuit parts with temperature ratings less than the cure temperature. The amine-amide cured epoxies are curable at lower temperatures (room temperature–100°C) but have a higher viscosity and a high exotherm temperature. The higher viscosities make it more difficult to degas and prevent bubbles and voids from occurring in the cured encapsulant. The exotherm temperature rises can be as high as 250°C and will damage low temperature rated circuit parts. Note that epoxy resistivity varies markedly during the curing process as in Figure 22; therefore, it is essential to be certain of a complete cure. Some typical anhydride formulations are:

Epon 828–10 parts by weight Linorid 8–9 parts by weight DMP 30–0.1 part by weight	48-hr cure at 70°C + 1 hr at 100°C
Stycast 1269/A–10 parts by weight Stycast 1269/B–10 parts by weight	16-hr cure at 100°C + 16 hr at 150°C

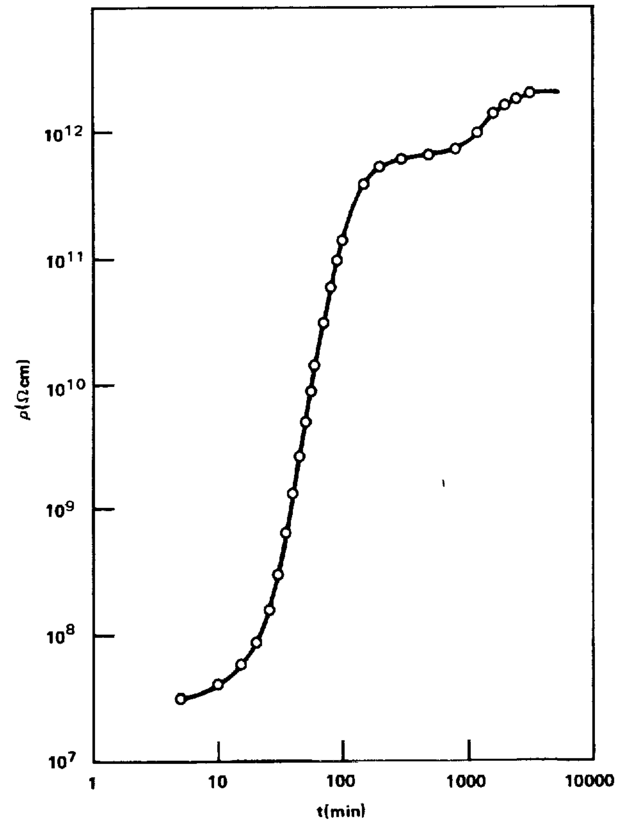


Figure 22. A Resistivity vs. Time Plot Showing Two Reactions Occurring at 80°C Using an Epoxide/Polyamide Ratio of 2g:1.5g. (Reference 16)

Some typical amine and amide formulations are:

Epon 828–10 parts by weight
(Teta) Triethylene Tetramine–1 part by weight

Epon 828–10 parts by weight
(DTA) Diethylene Triamine–1 part by weight

Epon 828–6 parts by weight
Versamide 140–4 parts by weight

Also ratios 7:3 and 1:1 can be used

Silicones

Silicone polymers also have additional characteristics which make them desirable encapsulants. These include superior electrical properties (dielectric constant = 3.0 to 5.0; dielectric strength = 300 to 600 volts/mil; volume resistivity = 10^{11} to 10^{14} ohm-cm; arc resistance = 300 to 450 s); excellent thermal properties (low degradation under continual exposure to temperatures greater than 200°C); a heat distortion temperature about

300°C; flexibility at low temperatures; no exotherm during the curing period; low mold shrinkage during cure (less than 0.005 in./in.); low viscosity and temperature coefficient of viscosity; low water absorption; long shelf and generally long pot life; and easy repairability.

Some silicone properties which can create design problems if neglected are a high temperature coefficient of expansion (200 to 400 $\times$ 10^{-6}/°C); a low thermal conductivity (3 to 5 $\times$ 10^{-4} cal/cm^2/s/cm/°C). Silicones are attacked by aliphatic and aromatic solvents and some mineral oils. Some of the volatile constituents of the silicones can be pyrolytically decomposed into silicon dioxide at elevated temperatures. This can be detrimental to bearings, gears, and so forth, in the neighborhood of the silicone resin. Other volatile constituents can also deposit out on optical surfaces and degrade optical and thermal behavior. The silicone encapsulants, which give off acetic acid during their cure, should not be used because the acid is corrosive to the circuitry.

Suitable silicone encapsulants for high-voltage spacecraft applications are DC 93-500, a 2-part unfilled silicone, and GE RTV 566, a filled phenylated polydimethyl siloxane.

Polyurethanes

Additional characteristics of the polyurethanes that make them desirable as potting and encapsulating polymers for high-voltage flight systems include good electrical properties (dielectric constant = 3 to 6, dielectric strength = 400 to 650 volts/mil, volume resistivity = 10^{12} to 10^{15} ohm-cm, arc resistance = 130 to 180 s); a good adhesion to most materials, although a primer coating on metals will insure a better bond; low water absorption; good heat resistance to about 125°C; low exotherm temperature rise (less than 55°C; low mold shrinkage (0.005 to 020 in./in.); long shelf life; long pot life; and easy repairability.

The linear thermal coefficient of expansion lies in the range 150 to 200 $\times$ 10^{-6}/°C greater than the epoxies but smaller than the silicones. The thermal conductivity falls in the range 2 to 6 $\times$ 10^{-4} cal/cm^2/s/cm/°C similar to those of the silicones and epoxies. These thermal properties should be considered when potting fragile components. Thermally induced stresses can cause component failure.

The preparation and handling of the polyurethanes should be performed with care since the prepolymers and curing agents can be health hazards. Chlorinated aniline curing agents (MOCA) should be avoided because they have been found to be carcinogenic. The prepolymers are isocyanates whose vapors can cause respiratory irritations. The repair of cured polyurethane potted systems, in which high temperatures are present (hot soldering iron), can generate cyanate and cyanide vapors which are highly toxic.

Operations with the polyurethanes should be performed in well ventilated, hooded areas. A polyurethane which has been highly successful as a high voltage encapsulant is Thiokol Corp. Solithane 113. It is a polyether based resin, which is more resistant to high humidity and cures at a lower temperature than polyester base urethanes.

Foams*

There are times when it becomes necessary to reduce the weight of spacecraft systems to keep within the allowable weight limits prescribed for a successful flight. One way this can be accomplished is to use foamed polymers as encapsulants thereby reducing the weight of the potted system. Where high-voltage systems are to be potted, it is not recommended that encapsulants be used that have been foamed by blowing gas methods. The void or bubble sizes in these foams are large and variable. This type of foam is conducive to a gas discharge, particularly where the voids are in large electric fields that exist in the neighborhood of small gaps between conductors, sharp points, or other geometric discontinuities of high-voltage conductors. A syntactic foam, one made by combining a resin with a hollow-sphere filler, is recommended when a foam is required. The hollow-sphere fillers, commonly known as microballoons or glass balloons, are very small and have a known size distribution (20 to 130, 30 to 125, 10 to 250 μm, and so forth). The probability of a breakdown occurring in these spheres is small, even in a comparatively high electric field, because the pressure in the small spheres is about 760 torr and the maximum gap is about 0.250 mm. This would require a voltage across the sphere of about 300 volts for a breakdown or an electric field of about 1200 volts/mil.

The balloons can be obtained in glass or ceramics, coated or uncoated. In selecting the suitable balloon, the coating should be checked to determine the effect on the electrical properties affecting high-voltage breakdowns (resistivity and dielectric constant). The addition of balloons greatly increases the viscosity of the polymers. This problem can be partly overcome by increased polymer temperatures during potting.

Resistivity and Voids

Although dielectric constant ratios determine the voltage distribution among layers of dielectrics in a capacitor with an applied a.c. potential, it is the resistivities that are important when considering d.c. potentials. As an example, consider the following simplified study of a parallel plate capacitor with three dielectrics in series (Figure 23). The middle dielectric will later be considered to be air at low pressure so that the model is that of a void in an encapsulant.

*Foams also are used to reduce mechanical stresses due to temperature changes.

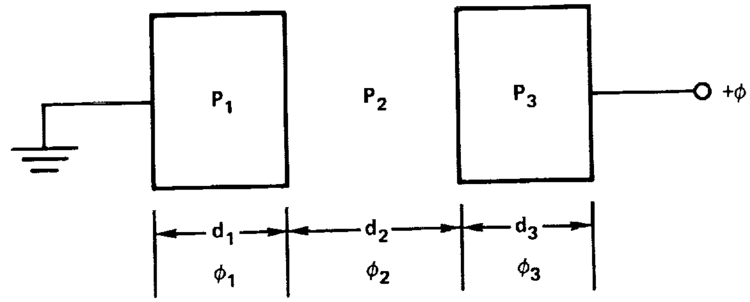


Figure 23. Simple Model of a Void.

The sum of the potential drops must be equal to the applied potential:

$$\phi = \sum_{i=1}^{3} \phi_i \, .$$

From symmetry and Ohm's Law it follows that the potential drop across each dielectric will be proportional to its thickness d_i and its resistivity P_i:

$$\phi_i = \frac{\phi \, P_i \, d_i}{\sum_i P_i \, d_i} \, .$$

The field is the negative gradient of potential, so

$$|\vec{E}_i| = \frac{\phi \, P_i}{\sum_i P_i \, d_i} \, .$$

Therefore, $|E| = \alpha \, P_i$ as would be expected.

If

$$P_1 = P_3 \ll P_2$$

then

$$|\vec{E}_2| \approx \frac{\phi}{d_2} \, .$$

That is, due to the conductivity of the dielectric, the capacitor plates effectively move in to the boundaries of the void thereby greatly increasing the intensity of the electric field in the void.

When the potential drop across the void reaches the corona onset voltage, a discharge occurs, followed again by gradual voltage buildup. The process repeats indefinitely leading to corona-induced degradation of the dielectric material. The repetition rate of this relaxation oscillator system can be estimated by use of the following equation adapted from Reference 17 for the special case of spherical voids.

$$f \approx 1.13 \times 10^{11} \left(\frac{\sigma}{\epsilon - 1}\right) \frac{E'}{E_i} ,$$

where σ is the volume conductivity of the encapsulant in mhos/m
ϵ is the dielectric constant of the encapsulant
E' is the applied electric field
E_i is the field across the void required to produce breakdown.

Putting typical values into the equation, that is,

$\epsilon = 2.3$

$E'/E_i = 1$

$\sigma = 5 \times 10^{-15}$ mho/meter

the result is

$$f \approx 4.35 \times 10^{-4} \text{ Hz} \approx 2 \text{ pulses/hr void.}$$

In this approximation it was assumed that the surface conductivity of the void is zero. This yields a maximum pulse rate for purposes of convenient calculations. The example illustrates the importance of making encapsulations void free. Pulse rates of this order have been observed on the outputs of spacecraft high-voltage power supplies. Laminar shaped voids in encapsulated systems can develop pulse repetition rates as high as double those of spherical voids. Note also that any sealed high-voltage connector necessarily contains voids and can therefore become degraded with time if under sufficient voltage stress, depending on the pressure in the void.

Bubbles Rising in Uncured Encapsulants

To illustrate the problems that can arise, even from initially small bubbles in encapsulants, consider Figure 24. This figure shows the diameter of a bubble in a typical encapsulant as a function of depth (Reference 18). The size of the bubble varies as it rises due to hydrostatic pressure. Note that,

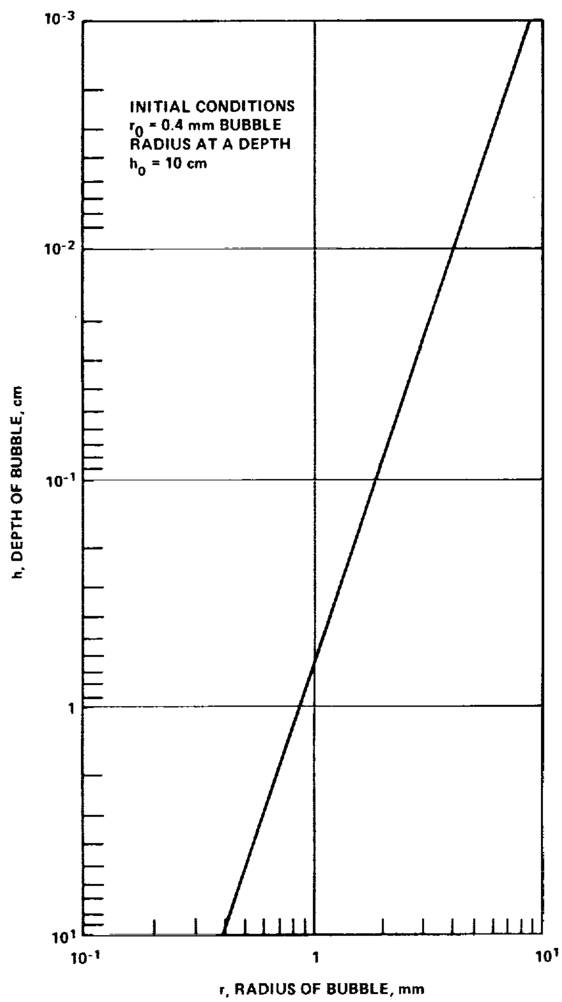


Figure 24. The Effect of Hydrostatic Pressure on the Size of a Bubble Rising in an Uncured Resin. From the relation $r = r_0\ (h_0/h)^{1/3}$. (Reference 18)

if a bubble rises far enough through the encapsulant such that the diameter doubles, the volume is multiplied by a factor of 8 causing the pressure inside the bubble to be reduced by a factor of 8. This implies that the pd product for the bubble becomes reduced by a factor of 4. Due to the doubling of the diameter the voltage drop across the bubble is doubled. These combined effects correspond, for example, to movement along the straight line in Figure 25. The criterion for prevention of breakdown in the bubble, therefore, is operation below the straight line, not merely below the Paschen curve. As an example, a bubble having an initial pd product of 1.0, as at A, will not breakdown because it is below the Paschen curve. However, the bubble can rise and expand such that its parameters trace the straight line path to B where intersection of the Paschen curve takes place

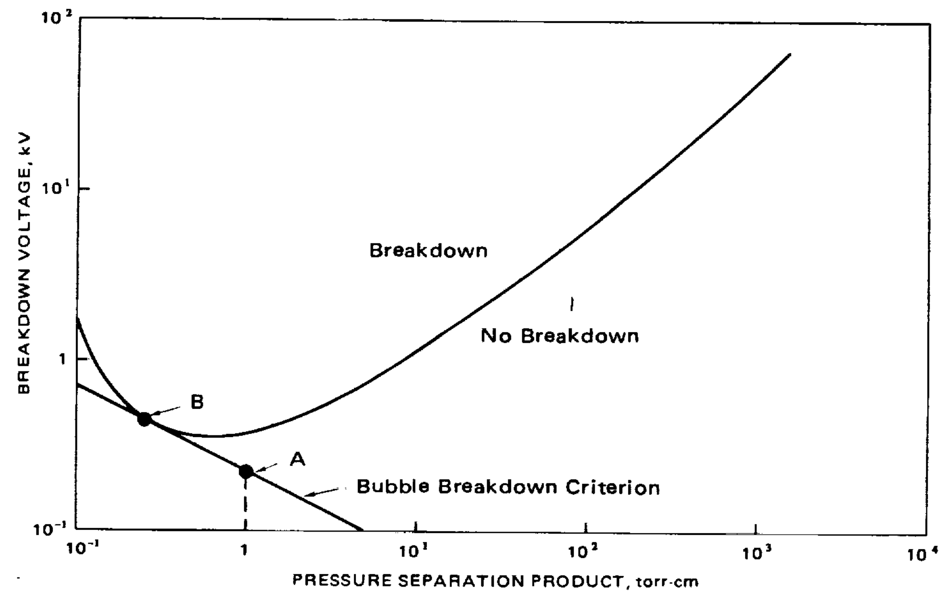


Figure 25. Typical Paschen Curve with Breakdown Criterion for Bubble Rising in Uncured Encapsulant.

and breakdown can occur. Bubbles initially smaller will trace paths parallel to the path shown, but will not intersect the Paschen curve and will not break down.

Poly Sandpile

One potting technique which helps to reduce the probability of trapping voids during encapsulation has recently been tested (J. E. Carey, Shell Development Company, private communication, 1973). It involves the use of μm-size glass spheres as a filler. Unlike the usual technique, the module to be potted is first filled with the dry filling material during mechanical agitation to ensure that the fine particles fill all recesses. A low viscosity encapsulation compound is then poured into the module under vacuum. The liquid flows through the filler by capillary action like water through a sponge. In addition to eliminating voids, the glass spheres almost entirely eliminate component breakage due to differential thermal expansion.

It is to be noted that high quality electrical grade glass spheres are preferable to alkali glass spheres. The presence of alkali ions on the latter can aid in causing voltage breakdown.

General Comments

The success of encapsulated high-voltage flight systems is dependent upon early planning, good engineering, careful system and hardware design, and meticulous care in fabrication. Close quality control should be exerted during the production stages. Because there are several manufacturers whose formulations are somewhat different for similar encapsulants, it is wise to read and adhere to the manufacturers instructions and recommendations regarding his materials and processes. The physical, electrical, and mechanical properties of some commonly used encapsulants are listed in Tables 4 and 5.

Table 4
Physical and Electrical Properties of Some Commonly Used Encapsulants

Material	Manufacturer	Coefficient of Thermal Exp. cm/cm °C $\times 10^{-4}$	Thermal Conductivity, cal/cm-sec °C $\times 10^{-4}$	Chemical Composition	Specific Gravity	Water Absorption Wgt %	Shore Hardness Number	Transparency and Color	Service Temperature Range (°C) from	to	Shelf Life Months
XR-5192	3M			Two part filled epoxy	1.53	0.36 (240 hours at 96% R.H.)	D72	Gray		+130	12
Scotchcast 235	3M	1.6	4.0	Unfilled epoxy	1.10	1.3 (1000 hour immersion)	D55	Brown		+130	12
Scotchcast 281	3M	1.5	12.0	Two part filled epoxy	1.43	0.4 (1000 hour immersion)	D65	Brown		+155	12
Scotchcast 3	3M	2.0	4.0	Unfilled epoxy	1.10	0.8 (1000 hour immersion)	D80	Clear		+130	12
RTV-11	GE	2.5	7.0	Silicone	1.18		A45	White	-59	+204	6
RTV-60	GE	2.1	7.4	Silicone	1.47		A60	Red	-59	+204	6
RTV-602	GE	2.9	4.1	Silicone	0.99		A15	Clear	-59	+204	6
RTV-615	GE	2.8	4.5	Silicone	1.02		A35	Clear	-59	+204	6
RTV-616	GE	2.7	6.6	Silicone	1.22		A45	Black	-59	+204	6
1090-SI	Emerson & Cuming	0.54	4.1	Epoxy resin syntactic foam	0.78	0.4 (24 hour immersion)	D78		-73	+107	6
3050	Emerson & Cuming	0.40	9.5	Epoxy resin	1.55	0.2 (24 hour immersion)	D88			+125	
EP-3	Emerson & Cuming			Two part epoxy resin			D80	Clear	-55	+120	6
IC-2	Emerson & Cuming			Two component urethane			A80	Clear	-55	+120	6
93-500	DOW	3.0	3.5	Silicone	1.08	<0.10 (7 day immersion	A46	Clear	-65	+200	12
XR-63-489	DOW	3.0	3.5	Two part silicone	1.05	<1.5 (7 day immersion)	A35	Clear	-55	+150	12
Sylgard-182	DOW	3.0	3.5	Two part silicone	1.05	0.1 (7 day immersion)	A40	Clear	-65	+200	12
Sylgard-184	DOW	3.0	3.5	Two part silicone	1.05	0.1 (7 day immersion)	A35	Clear	-65	+200	6
Sylgard-186	DOW			Two part silicone	1.12	0.1 (7 day immersion)	A32	Translucent	-65	+250	6
RTV-3140	DOW		2.9	One part silicone	1.06	0.4 (7 day immersion)	A21	Clear	-65	+250	6
RTV-3145	DOW		4.0	One part solicone	1.12	0.4 (7 day immersion)	A33	Gray	-65	+250	6
K230	CONAP		5.0	Two part epoxy	~1.4	0.37 (24 hour immersion)	D65-70	Clear			12
CE-1155	CONAP			Two part solvent-based polyurethane			Sward 70	Clear	-130		12
Epon 828-Versamid 140 50% - 50%	Shell Gen.Mills			Two part epoxy			Rockwell M 80				
Solithane 113	Thiokol			Urethane prepolymer	1.07	~0.2 (24 hour immersion)	A-35 to D-60	Clear		+121	
Humiseal 1B12	CTC			One part, 20% solids acrylic	1.05	0.18 (24 hour immersion			-59	+138	12
2# Custom Foam 6-1104	Rogers Foam		0.83	Polyester-Polyurethane				Black			
Uralane 8267	Furane			One component urethane				Clear			6
B-6-640-1	Westinghouse							Red			<12

*For dielectric constant of 3.00, the test frequency is 100 kHz.

Table 4 (continued)
Physical and Electrical Properties of Some Commonly Used Encapsulants

Material	Dielectric Constant	Dissipation Factor	Test Frequency	Dielectric Strength, Volts/mil	Arc Resistance Seconds	Surface Resistivity ohm-cm	Volume Resistivity ohm-cm
XR-5192	4.62	3.1	100 Hz	276	168		1.5×10^{13}
Scotchcast 235	5.2	0.05	100 Hz	325			1×10^{15}
Scotchcast 281	4.9	0.05	100 Hz	375			$>1 \times 10^{14}$
Scotchcast 3	3.3	0.005	100 Hz	300			$>1 \times 10^{15}$
RTV-11	3.6	0.019	60 Hz	500	≥ 100	$\sim 10^{15}$	6.0×10^{14}
RTV-60	3.7	0.020	60 Hz	500	$\gtrsim 100$	$\sim 10^{15}$	1.3×10^{14}
RTV-602	3.0	0.001	60 Hz	500	$\gtrsim 100$	$\sim 10^{15}$	1.0×10^{14}
RTV-615	3.0	0.001	60 Hz	500	≥ 100	$\sim 10^{15}$	1.0×10^{15}
RTV-616	3.0	0.001	60 Hz	500	$\gtrsim 100$	$\sim 10^{15}$	1.0×10^{15}
1090-SI	3.7 3.1 2.9	0.02 0.01 0.01	60 Hz 1 kHz 1 MHz	375			1×10^{13}
3050	4.4 4.2 3.9	0.01 0.02 0.04	60 Hz 1 kHz 1 MHz	400			1×10^{14}
EP-3	4.4	0.006	1 kHz	400			$10^{13}\Omega$/square
IC-2	5.0 5.0	0.04 0.04	60 Hz 100 MHz	>400			$>1 \times 10^{12}$
93-500	2.75 2.73	0.0011 0.0013	100 Hz 100 kHz	570			6.9×10^{13}
XR-63-489	2.88 2.88	0.002 0.002	100 Hz 10 kHz	500	115	3.6×10^{14}	1×10^{14}
Sylgard-182	2.70 2.70	0.001 0.001	100 Hz 1 MHz	550	115		2.0×10^{14}
Sylgard-184	2.75 2.75	0.001 0.001	100 Hz 1 MHz	550	115		1.0×10^{14}
Sylgard-186	3.01 3.00	0.0009 0.001	100 Hz 1 MHz*	575		$>7 \times 10^{16}$	2×10^{15}
RTV-3140	2.64 2.63	0.0016 0.0006	100 Hz 1 MHz	500	50		5×10^{14}
RTV-3145	2.81 2.78	0.0015 0.0028	100 Hz 1 MHz	600	50		5.0×10^{14}
K230	3.35	0.03	1 MHz	2000 (5 mil film)		1.25×10^{14}	1×10^{14}
CE-1155	3.50 3.43	0.0142 0.0138	100 Hz 1 kHz	3000 (2 mil film) 1045 (22 mil film)		5.66×10^{14}	1.18×10^{16}
Epon 828-Versamid 140 50% - 50%	3.23 3.19 2.99	0.0036 0.0070 0.019	60 Hz 1 kHz 1 MHz			5.5×10^{15}	1.22×10^{16}
Solithane 113	2.8-5.0	0.014-0.162	1 kHz @ 80°F	340-512		1.5×10^{15}	7×10^{12} to
	4.5-5.1	0.006-0.079	1 kHz @ 185°F				3.6×10^{14}
Humiseal 1B12	2.8	0.01	1 MHz	6000V. (MIL-I-46058B)			2.5×10^{14}
2# Custom Foam	97% voids intercon-necting cells						
Uralane 8267	4.4 3.6	0.049 0.053	1 kHz 1 MHz	2500 (3 mil film)	149		3.0×10^{12}
B-6-640-1				1200 (5 mil film)	126	2×10^{13}	

Table 5
Mechanical Properties of Some Commonly Used Encapsulants

Material	Tensile Strength (kpsi.)	Tensile Elongation, %	Pot Life, hours	Viscosity, Poises	Principal Characteristics
XR-5192	0.995	75			High arc and track resistance
Scotchcast 235	1.3	75	0.25	15	Low viscosity, permanent flexibility
Scotchcast 281	2.1	45	0.3	480	Permanent flexibility, high temp. stability
Scotchcast 3	4.4	1.8	0.3	16	Lowest viscosity, excellent electrical properties
RTV-11	0.35	180	1-6	120	Flexible
RTV-60	0.80	130	1-5	500	Flexible, high temperature
RTV-602	0.10	200	0.5-8	12	Transparent
RTV-615	0.925	150	~4	40	Transparent, high temperature
RTV-616	0.925	125	~4	90	High temperature
1090-SI				18	Low density
3050				5	Low viscosity
EP-3			6	2.4	Surface coating, good mechanical and water resistance
IC-2		400		4.0	Surface coating, good mechanical and water resistance, high temperature
93-500	0.790	110	1	80	Low weight loss in hard vacuum
XR-63-489	0.90	100	8	50	Transparent, flexible, for laminating glass
Sylgard-182	0.90	100	8	30	Low viscosity, low cure shrinkage, wide temperature range
Sylgard-184	0.90	100	2	30	Low viscosity, low cure shrinkage, wide temperature range
Sylgard-186	0.70	420	2	450	High strength, wide temperature range
RTV-3140	0.30	350		350	Clear conformal coating, no acetic acid evolved during cure
RTV-3145	0.70	675			Clear, high strength, noncorrosive, wide temperature range
K230	2.0		1-1.5		Clear epoxy, kit form
CE-1155			6	.72	Coating with good moisture and abrasion resistance
Epon 828-Versamid 140 50% - 50%	8.3	3.9 (?)		~160	
Solithane 113	0.16-3.2	60-120	0.3-8	200	Versatile, soft to extremely rigid depending on catalyst used
Humiseal 1B12 2# Custom Foam 6-1104				0.3 stokes	Low viscosity coating Excellent vibration and shock protection
Uralane 8267				1.5-3.0	Repairable, solder-through, transparent coating
B-6-640-1			12		Tough, resilent nontracking surface coating

CIRCUIT BOARDS

The construction of most small, high-voltage power supplies used in space applications involves the use of circuit boards. The most popular board materials are epoxy impregnated fiberglass, types G-10 and G-11. The latter is apparently slightly superior.

Data for voltage breakdowns between adjacent conductors on circuit boards seem to be unavailable,* so a simple breakdown test was performed at GSFC. A test circuit board was constructed using the same techniques employed for space-rated boards. The etched circuit pattern consisted of several 4-inch straight, parallel conductors spaced 0.5 mm, 1.0 mm, and 2.5 mm apart. Voltages were applied to the electrodes inside a vacuum bell jar via insulated wires and a vacuum feedthrough from an external high-voltage power supply. A cathode ray oscilloscope (CRO) in series with the ground return lead was employed for monitoring breakdown, leakage, and corona currents. Sensitivity was such that a current as low as 10^{-9} A could be readily measured. Pressure was $\sim 2 \times 10^{-7}$ torr.

Test results indicate that an uncoated board fabricated of G-11 material is corona free with applied voltages and circuit element spacings such that the ratio: volts applied/spacing = 10 kV/mm.* This does not imply that 100 kV could be successfully applied to electrodes separated 10 mm apart, however, due to high field emission at the sharp edges of the conductors. A value of ~20 kV appears to be the practical limit for uncoated boards with reasonable (~1 cm) conductor spacing. Results of tests conducted with the same board after coating with Solithane 113 indicate that ~15 kV/mm is an upper limit for coated boards. Above this value, random current spikes of up to 5×10^{-7} A were observed, although no catastrophic breakdowns occurred. At 40 kV/mm (20 kV, 0.5 mm), a gradually increasing direct current of $\sim 2 \times 10^{-8}$ A was noted. This was undoubtedly caused by nonuniform leakage currents causing localized heating of the Solithane 113 coating.

Figure 26 is a plot of corona onset voltage versus pressure for the same (uncoated) circuit board described above. These curves can shift to much lower voltages when fingerprint contamination is present. This is readily understandable on the basis of the resistance versus humidity curves of Figure 27. Note that surface resistivities can shift by over two orders of magnitude, illustrating the importance of cleanliness during handling procedures. These curves also suggest that drying of circuit boards in a hard

*Measurements made by R. S. Bever, Private Communication, GSFC, August 1973, indicate a flashover value of about 2 kV/mm at 1 atmosphere of ordinary air. The boards tested were not thoroughly outgassed; however, this discrepancy emphasizes the importance of adsorbed water vapor in determining surface flashover voltages.

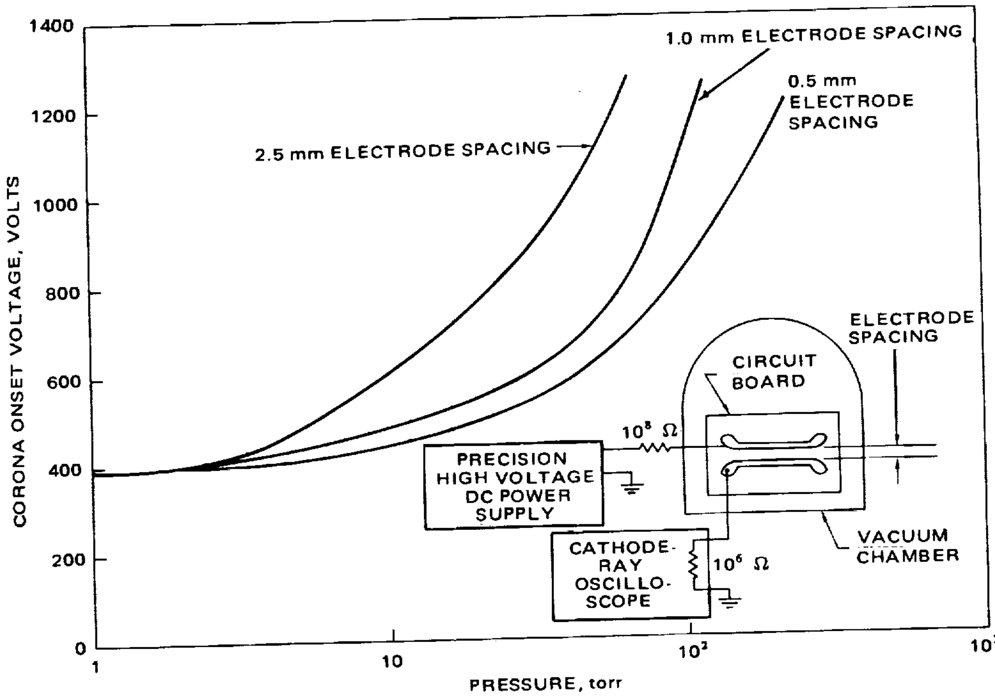


Figure 26. Corona Onset Voltage for Parallel Conductors on G-11 Circuit Board.

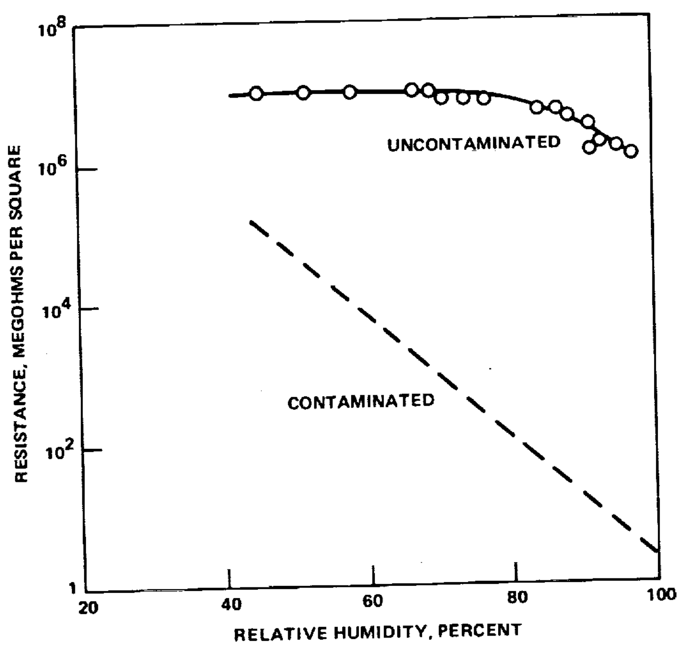


Figure 27. Surface Resistance of Epoxy Resin Fiberglass Laminated Board as Affected by Fingerprint Contamination When Exposed to Air at High Humidity.

vacuum just prior to conformal coating is a desirable procedure. Various mechanical, physical, and electrical properties for circuit board materials are included in Table 6. Table 7 is a listing of properties of some common coating materials (Reference 19).

DEPRESSURIZATION AND OUTGASSING

Unpotted power supplies are generally built with the electronic components mounted inside a metal box. (See Reference 20 for discussion of Outgassing and Pressure.) A question of practical importance involves the amount of perforation of the box required for reasonably fast depressurization to assure that low enough pressures will exist prior to supply turn-on. From simple effusion theory it can be shown that the pressure inside the box, with zero outside pressure, is

$$p(t) = p(o)\, e^{-\left(\frac{\bar{v} A t}{4V}\right)}$$

where
- $p(o)$ is the initial pressure in the box at $t = o$,
- A is the total area of the perforations,
- t is the time,
- V is the volume of the box,
- $\bar{v}$ is the mean molecular speed; that is,

$$\bar{v} = \sqrt{\frac{8\,kT}{\pi m}}$$

in which

- k is the Boltzmann constant,
- T is the absolute temperature, and
- m is the mass of a gas molecule.

For nitrogen at room temperature,

$$\bar{v} \approx 4.6 \times 10^4 \text{ cm/s}.$$

A useful guide is derived by noticing that the time constant in the above exponential becomes

$$\tau \approx 0.1\ V/A$$

when
- V is measured in liters,
- A is measured in cm^2,
- T is room temperature ($T = 20°C$), and
- the gas is air or N_2.

This rule, coupled with use of Figure 28, can simplify depressurization time calculations. As an example, a 10-cm-radius sphere with a 1-cm^2 opening has a time constant of ~0.4 s. Using Figure 28, one finds immediately

Table 6
Properties of Laminated and Reinforced Plastics

NEMA Grade	Min. Flexural Str., 1/16", psi		Min. Izod Impact Str., ft-lb/in notch, edge		Min. Bond Str., lbs.	Water Abs., Max., 1/16" %	Min. Diel. Str., § kv.	Max Diel. Const., 1 MHz 1/32" or more	Thermal Coeff. of Exp. cm/cm °C X10⁻⁴	Max Diss. Factor, 1 MHz 1/32" or more	Min. Arc Resist., secs.	Tensile Str., psi	
	LW (X10³)	CW (X10³)	LW	CW								LW (X10³)	CW (X10³)
X	25	22	0.55	0.50	700	6.00						20	16
XP	13	11				3.60	40					12	9
XPC	10	8				5.50						10.5	8.5
XX	15	14	0.40	0.35	80	2.00	40	5.5		0.045		16	13
XXP	14	12			0	1.80	60	5.0		0.040		11	8.5
XXX	13.5	11.8	0.40	0.35	950	1.40	50	5.3		0.038		15	12
XXXP	12	10.5				1.00	60	4.6		0.035		12.4	9.5
XXXPC	12	10.5				0.75	60	4.6		0.035			
ES-1	13.5	13.5	0.25	0.22		2.50							
ES-2			0.25	0.22									
ES-3	13.5	13.5	0.25	0.22		2.50							
C	17	16	2.10	1.90	1800	4.40	15					10	8
CE	17	14	1.60	1.40	1800	2.20	35					9	7
L	15	14	1.35	1.10	1600	2.50	15					13	9
LE	15	13.5	1.25	1.00	1600	1.95	40	5.8		0.055		12	8.5
A	13	11	0.60	0.60	700	1.50	5					10	8
AA	16	14	3.60	3.00	1800	3.00						12	10
G-3	20	18	6.5	5.5	850	2.70						23	20
G-5	50	40	7.0 (to 1/2")	5.5	1570	2.70	23	7.8		0.020	180	37	30
G-7	20	18	6.5	5.5	650	0.55	32	4.2		0.003	180	23	18.5
G-9	60	40	13.0	8.0	1700	0.80	60	7.5		0.018	180	40	25
G-10	60	50	7.0	5.5	2000	0.25	45	5.2		0.025	128	35	30
G-11	60	50	7.0	5.5	1600	0.25	45	5.2		0.025	115	35	30
N-1	10	9.5	3.0	2.0	1000	0.60	60	3.9		0.038		8.5	8
FR-2	12	10.5				0.75	60	4.6		0.035		12.4	9.5
FR-3	20	16				0.65	60	4.6		0.035		12	9
FR-4	60	50	7.0	5.5	2000	0.25	45	5.2	1.5	0.025	128	35	30
FR-5	60	50	7.0	5.5	1600	0.25	45	5.2	1.5	0.025	128	35	30
GPO-1	18	18	8.0	8.0	850	1.00	40	4.3		0.03	100	12	10
GPO-2	18	18	8.0	8.0	850	0.9	40				100	10	9
Dialyte‖	40						35	4.0	0.13	0.008	>60		
	50						35	4.8	0.1	0.020	180		
Polyimide‖													
Fluorglas‖	15	11				0.05		2.54	0.1	0.0008	180	19	15
Rexolite‖	11.5	11.5	0.3			0.05		2.53	0.7	0.00012		7	7
AL300‖	71	55	19	18	2000	<0.25		4.0	0.1	0.02	180	40	40

All tests conducted in accordance with applicable NEMA and/or ASTM standards.

- * See NEMA Pub. No. LI 1-1971, Standards Publication for Industrial Laminated Thermosetting Products, regarding test methods, conditions, etc.
- † Usually made with these resins. These grades are engraving stock.
- ‡ These are only typical values obtained from a number of sources and should not be used in establishing specifications or standards–consult manufacturers.
- § Parallel to lamination, Step-by-Step, 1/16" thick.
- ‖ Atlantic Laminates Co. data

Table 6 (continued)
Properties of Laminated and Reinforced Plastics

NEMA Grade	Compr. Str., psi Flat ($\times 10^3$)	Compr. Str., psi Edge ($\times 10^3$)	Rockwell Hardness M Scale	Sp. Gr.	Diel. Str., Perp. to Lam., vpm Short time	Diel. Str., Perp. to Lam., vpm Step by Step	Thick. Range Inch min.	Thick. Range Inch max.	Base Material	Volume Resistivity ohm-cm	Resin	Surface Resistance, Megohms (BS1137, Appendix H)
X	36	19	110	1.36	700	500	.010	2	Paper		Phen.	
XP	25		95	1.33	650	450	.010	1/4	Paper		Phen.	
XPC	22		75		600	425	1/32	1/4	Paper		Phen.	
XX	34	23	105	1.34	700	500	.010	2	Paper		Phen.	
XXP	25		100	1.32	700	500	.015	1/4	Paper		Phen.	
XXX	32	25.5	110	1.32	650	450	.015	2	Paper		Phen.	
XXXP	25		105	1.30	650	450	.015	1/4	Paper		Phen.	
XXXPC	25		105	1.31	650	450	1/32	3/16	Paper		Phen.	
ES-1				1.58			3/64	1/4			Mel.†	
ES-2				1.46			.085	1/4			Phen.†	
ES-3				1.48			3/64	1/4			Mel.†	
C	37	23.5	103	1.36	150		1/32	10	Cotton		Phen.	
CE	39	24.5	105	1.33	500	300	1/32	2	Cotton		Phen.	
L	35	23.5	105	1.35	150		.010	2	Cotton		Phen.	
LE	37	25	105	1.33	500	300	.015	2	Cotton		Phen.	
A	40	17	111	1.72	225	135	.025	2	Asb. Paper		Phen.	
AA	38	21	103	1.70			1/16	2	Asb. Fabric		Phen.	
G-3	50	17.5	100	1.65	700	500	.010	2	Cont. Gl.		Phen.	
G-5	70	25	120	1.90	350	220	.010	3 1/2	Cont. Gl.		Mel.	
G-7	45	14	100	1.68	400	350	.010	2	Cont. Gl.		Sil.	
G-9	65			1.90	400	350			Cont. Gl.		Mel.	
G-10	70	30	110	1.75	700	500	.010	1	Cont. Gl.	$>10^{12}$	Epoxy	$>10^4$
G-11	70	30	110	1.75	700	500	.010	1	Cont. Gl.	$>10^{12}$	Epoxy	$>10^4$
N-1	28		105	1.15	600	450	.010	1	Nylon		Phen.	
FR-2	25		105	1.30	650	450	.030	1/4	Paper		Phen.	
FR-3	28			1.45	600	500	1/32	1/4	Paper		Epoxy	
FR-4	70	30	110	1.75	700	500	.010	1	Cont. Gl.	$>10^{12}$	Epoxy	$>10^4$
FR-5	70	30	110	1.75	700	500	.010	1	Cont. Gl.	$>10^{12}$	Epoxy	$>10^4$
GPO-1	30	20	100	1.5-1.9	400		1/16	2	Gl. Mat		Polyes.	
GPO-2	30	20	100	1.5-1.9			1/16	2	Gl. Mat		Polyes.	
Dialyte‖					750				Gl.	$>5\times10^{14}$	Polyes.	$>9\times10^8$
Polyimide‖					750				Gl.	$>6\times10^{10}$	Polyimide	$>6\times10^4$
Fluorglas‖					45kv/ 1/16"					$>10^{12}$	PTFE	$>10^4$
Rexolite‖				1.05	30kv/ 1/16"					$>10^{16}$	Styrene Copolymer	$>10^8$
AL300‖	77	35	115		1000				Glass	$>10^{14}$	Polyimide	12×10^5

All tests conducted in accordance with applicable NEMA and/or ASTM standards.

* See NEMA Pub. No. LI 1-1971, Standards Publication for Industrial Laminated Thermosetting Products, regarding test methods, conditions, etc.

† Usually made with these resins. These grades are engraving stock.

‡ These are only typical values obtained from a number of sources and should not be used in establishing specifications or standards - consult manufacturers.

§ Parallel to lamination, Step-by-Step, 1/16" thick.

‖ Atlantic Laminates Co. data

Table 7
Typical Properties of Common Coating Materials

Base polymer	Surface resistivity	Relative permittivity (60 Hz-1 MHz)	Dissipation factor (60 Hz-1 MHz)	Solderability	Resistance to humidity	Resistance to chemicals
	Ω					
alkyd	10^{12}	3-9	0-505	fair	excellent	good
Acrilan	10^{13}	4-0	0-015	good	good	fair
epoxide (room-temp. cure)	10^{13}	3-6	0-020	fair	good	good
epoxide (elevated temp. cure)	10^{14}	4-0	0-010	poor	excellent	excellent
polyurethane	10^{11}	4-5	0-025	fair	good	good

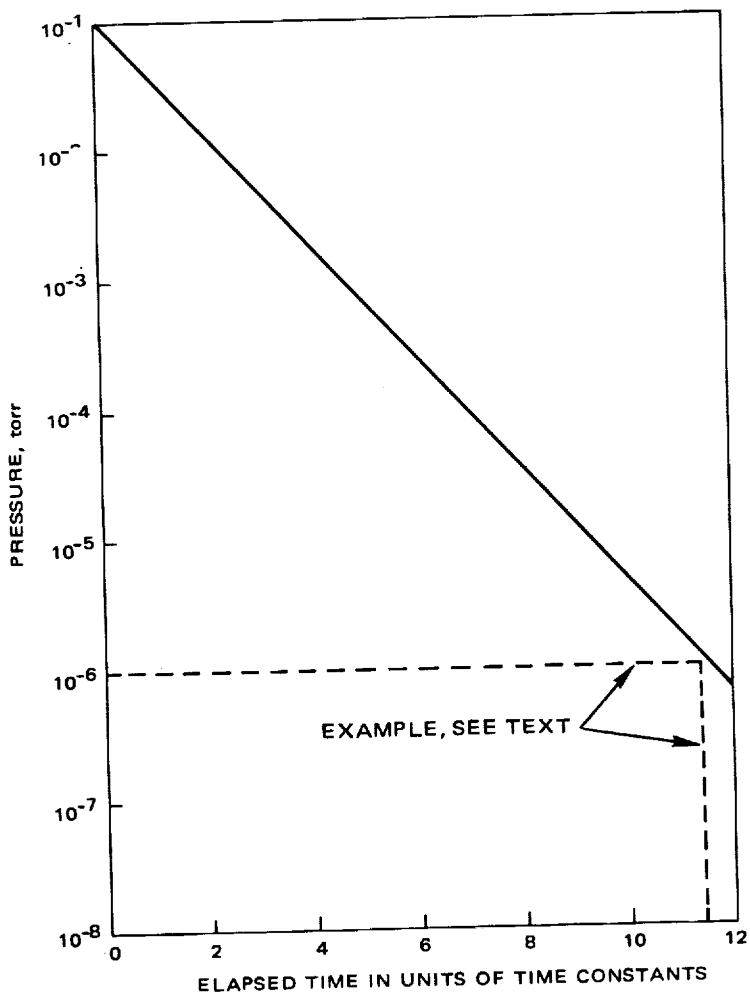


Figure 28. Pressure vs. Time (Simple Effusion Theory, see text).

that the pressure will drop from 10^{-1} to 10^{-6} torr in about 11 time constants, or about 4.5 s. Of course, material- and temperature-dependent outgassing of the surfaces inside the container can considerably lengthen the depressurization time as illustrated in Figures 29, 30, and 31 (Reference 21).

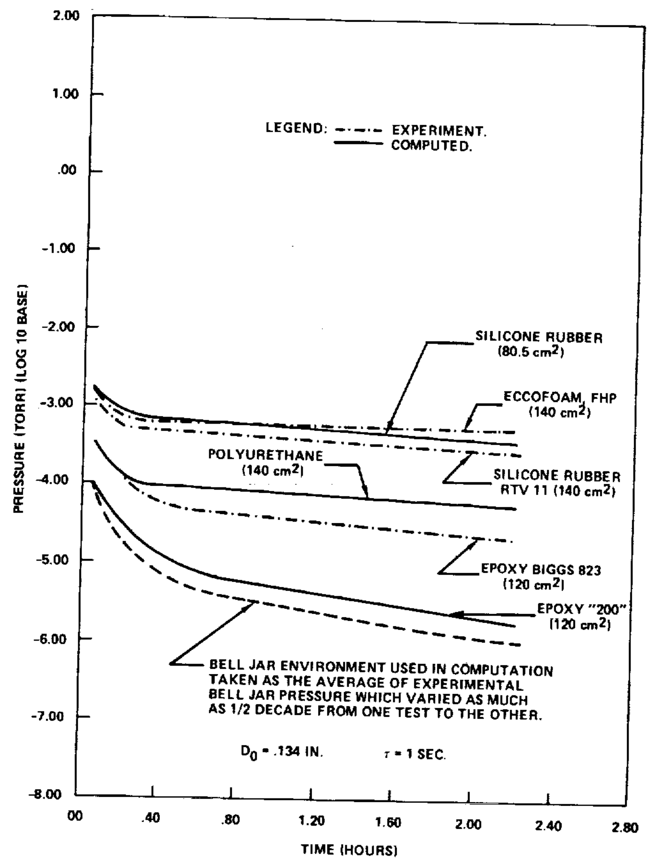


Figure 29. Comparison of Experimental and Computed Results for a 1-liter Compartment with Orifice Diameter 0.134 in., τ = 1.0 s, Ambient Temperature. (Reference 21)

A handy design figure is to provide a V/A = 10,000 cm to achieve approximately a one second time constant. Here the value of V must be in cubic centimeters and the value of A must be in square centimeters. This V/A value should be increased by a factor of 2 or 3 if the outgassing passages are labyrinthine.

As described in Reference 21 and illustrated in Figures 29, 30, and 31, after the initial depressurization period of about one hour, the pressure decreases much more slowly with a combination of an exponential time dependence (first order surface desorption), a $t^{-1/2}$ dependence (diffusive processes in outgassing of elastomers or outgassing of glass), and a t^{-1} dependence due to outgassing of metals. The net results for a 1-liter glass cylinder containing a sample of RTV-11 was an approximately exponential decay with a 3-day outgassing time constant. Note

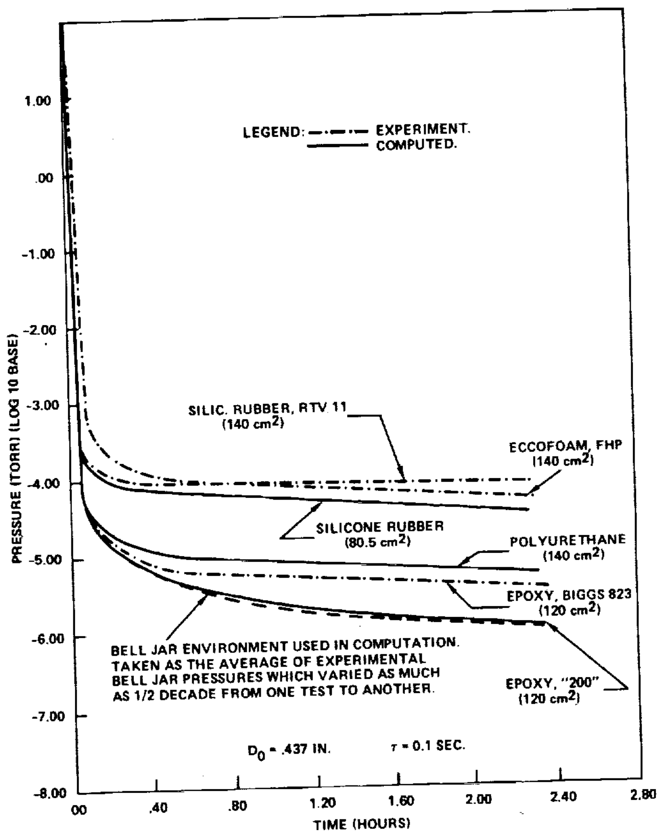


Figure 30. Comparison of Experimental and Computed Results for a 1-liter Compartment with Orifice Diameter 0.437 in., τ = 0.1 s, Ambient Temperature. (Reference 21)

that the pressure remained near the corona region for several hours (Figure 31) when the chamber time constant was adjusted to 10 s.

COMPONENT CONSIDERATIONS

Documents, specifications, and lists of component types that have been screened and approved for space flight use are available. Use of these guides does not, however, eliminate all the difficulties which can occur in the final application of these components. The following descriptions illustrate some of these problems.

Resistors

High-voltage resistors used successfully in spacecraft power supplies include Victoreen MOX1125, Caddock MG680, RPC type BBMW, and Caddock MG721.

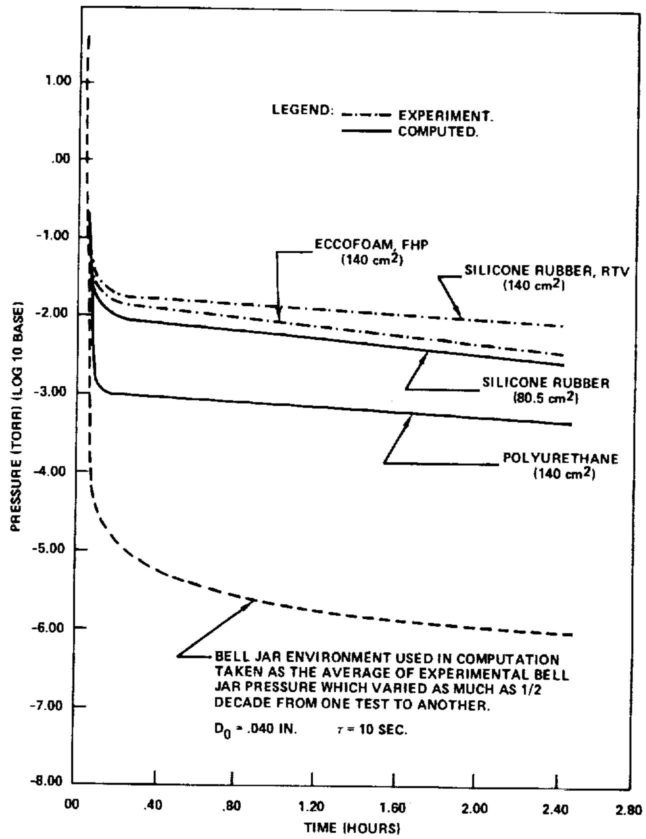


Figure 31. Comparison of Experimental and Computed Results for a 1-liter Compartment with Orifice Diameter 0.040 in., τ = 10 s, Ambient Temperature. (Reference 21)

One well known difficulty experienced with high-voltage film resistors involves corona developed in gases trapped in hollow ceramic cores. Another less known (suspected) problem involves the inductance caused by the helical form of the resistance element. Current surges through such elements due to sparking elsewhere in the circuit may cause resistor failure due to the resonance action of the inductance with circuit capacitance. Where such a failure mechanism is suspected, the serpentine form (noninductive) film resistors manufactured by Caddock (Figure 32) may provide a solution.

An unusual problem encountered during cleaning operations involved MOX1125 resistors. It was found that the cleaning solvent employed, trichlorethylene, dissolved the blue coating material on the resistor bodies.

Diodes

Diodes favored by the designers interviewed include 1N649's, 1N4586's, Semtech SFM-70 7KV, SFM-25 2.5 kV, Semtech 1N5184, and Microsemiconductor MC002.

One problem noted with plastic molded diodes is the slow diffusion of moisture onto the diode junction over a period of years.

The designer should be wary also of gas leakage from glass-cased diodes. This can lead to corona inside potted modules. Two problems have developed with the microminiature epoxy bead diodes. One is a quality control problem having to do with the proper alignment of the ribbon leads during insertion into the bead. The other problem involves breakage of junction leads due to thermal expansion at temperature extremes.

Capacitors

Capacitors used successfully by the designers interviewed include high voltage ceramic discs manufactured to several EIA specified dielectric formulations including X5P; X5R; W5R; and Z5U. Manufacturers include Centralab, Erie, and Sprague.

Difficulties have been experienced with porous epoxy coated disc ceramic capacitors. Standard varieties are supplied by the manufacturer with a wax impregnated durez coating which prevents adhesion of encapsulants. The wax coating is difficult to remove, but if uncoated units were employed it was found that corona problems developed. In one case, capacitors used for filtering proved self-defeating because they were themselves sources of noise due to corona. Coatings such as the Erie "Jet Seal" hard epoxy coating and the Centralab blue Hysol XDK-R13 epoxy coating do not exhibit this undesirable behavior.

An unusual problem involves high current degradation in Mylar capacitors. Apparently, high surge currents can evaporate some of the metal coating on the Mylar film, resulting in reduced capacitance. If used, this type of capacitor should not be allowed to become short-circuited or otherwise subjected to large currents.

Another problem which designers have encountered is the very large variation of capacitance with applied voltage and with temperature exhibited by the X5U; W5R; and Z5U dielectric formulations for ceramic discs. Some typical capacitance curves which illustrate these effects are given in Figures 33 and 34.

The combined effects of high voltage and extreme temperatures can render a Cockroft-Walton multiplier inoperative because of the severe reduction in the capacitance. The obvious solution is to overdesign both in the direction of higher voltage and in the direction of higher capacitance once a dielectric material has been chosen.

Connectors

The problem of connecting high-voltage power supplies to the spacecraft instruments being powered is far from trivial. Standard or specially fabri-

Figure 32. Caddock Serpentine Film Resistor.

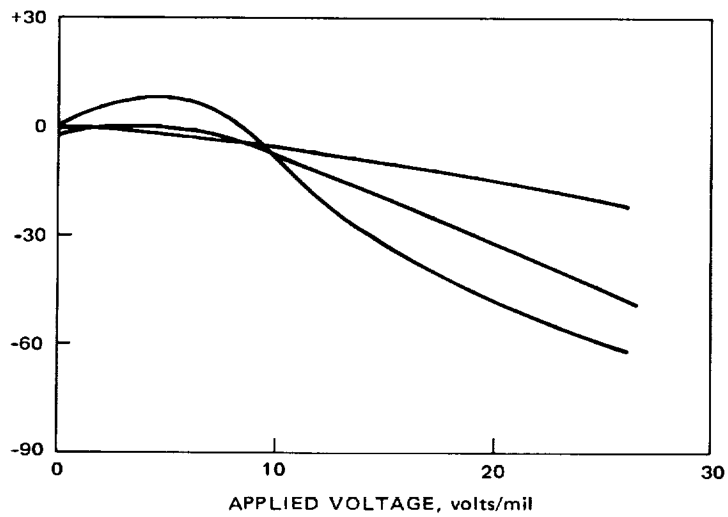


Figure 33. Capacitance Variation with Voltage (ceramic dielectric).

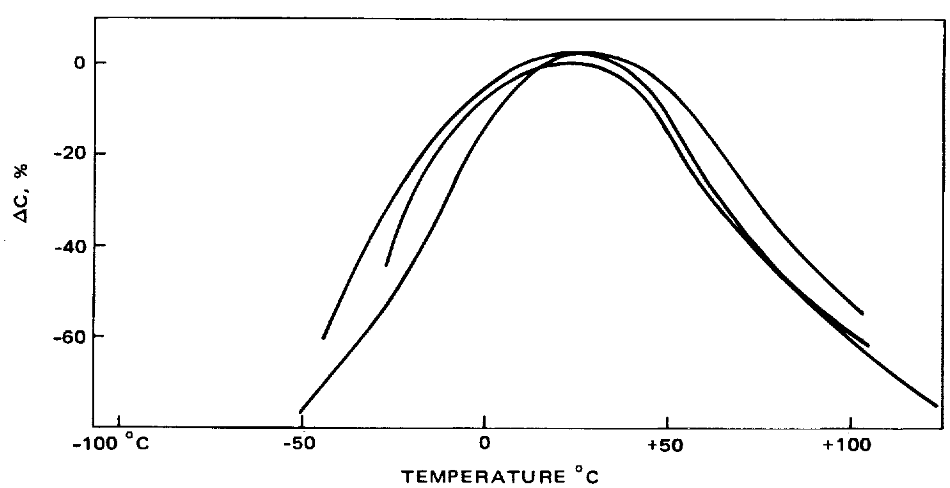


Figure 34. Capacitance Variation with Temperature (ceramic dielectric)
EIA-Z5U formulation.

cated high-voltage connectors have been used with some success when modified for the space environment; that is, by drilling holes to allow for adequate venting. Usually, however, connectors have been specially designed or designed out of the system entirely in order to avoid corona problems. This leads to difficult and inconvenient assembly and testing.

A new type subminiature (0.25-in. O.D.) connector, Reynolds Industries, Series 600, is available for voltages up to 10 kV and any pressure from atmospheric to hard vacuum. The male connector features a diallyl phthalate liner the whole length of the cylindrical wall (Figures 35 and 36). In addition, an O-ring around the base of the pin seals against the center insulator of the female connector. This construction results in long leakage paths and almost total immunity to corona. A sample pair of connectors was tested for one week at GSFC at 10 kV, both polarities, at several pressures from atmospheric to 5×10^{-7} torr. No corona or voltage breakdowns were observed. Designers are urged to consider this type of connector for use in future spacecraft.

Figure 35. Reynolds High-Voltage Connector.

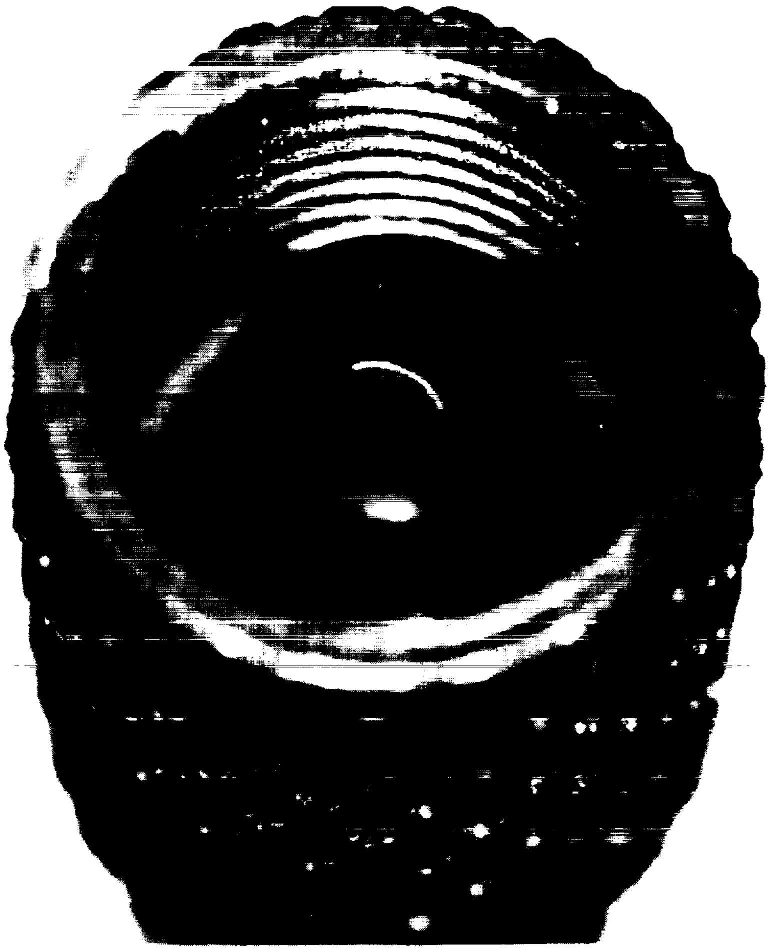


Figure 36. Reynolds High-Voltage Connector.

CURRENT DESIGN PRACTICE

This section presents electrical and mechanical design practices that are currently accepted and that are based on the theories and data presented earlier in this document. Examples of successful power supplies are discussed.

ELECTRICAL DESIGN

Small high-voltage power supplies designed to supply current to spacecraft-borne photomultiplier tubes and particle analyzers have employed the oscillator-Tesla coil (resonant transformer) Cockroft-Walton multiplier combination almost exclusively. The reasons given for not choosing other techniques include considerations of efficiency and the high-voltage ratings of components.

The Cockroft-Walton circuit divides the total output potential into a number of smaller potential increments. Each diode and capacitor is subjected to one of these increments instead of to the total output potential.

Several useful articles relevant to the design of Cockroft-Walton multipliers exist (References 22, 23, and 24). The article by Weiner (Reference 24) includes a derivation of the output voltage as a function of the number of stages n, the frequency f, and the capacitance C. (All capacitors assumed equal):

$$V = n\,V_{in}\left(1 - \frac{4n^2 + 3n^{-1}}{6fC}\right).$$

The author notes that, for maximum efficiency, the capacitance values should be tapered, the first capacitor in the chain having n times the capacitance of the *nth*. This could mean an important weight and space saving for spacecraft applications where some of the capacitors near the top of the chain would be physically smaller than the ones at the bottom. The article by Rumble (Reference 24) gives a useful summary of all possible voltage multiplier arrangements.

It is well known that when a charged capacitor is connected to an equal but uncharged capacitor, half of the charge transfers to the second capacitor. Also, half of the energy is radiated away from the system and lost. The paper by Mostov et al. (Reference 25) includes design curves and describes techniques for reducing these losses which can be appreciable in the case of the energy transfer to an arc jet or other high power device.

MECHANICAL DESIGN

Current design practice involves the use of epoxy impregnated fiberglass circuit boards almost exclusively for supplies with output voltages below approximately 3 kV. Circuit boards are being used, with modifications, up to about 15 kV. These modifications include potting and conformal coating of high-voltage sections of the circuit boards (front and back), milling slots through boards to lengthen surface breakdown paths, and mounting the components that are subject to high-voltage stress on stand-offs to eliminate surface breakdown problems. Type G-11 board material has been found to be preferable to type G-10 because of increased leakage resistance. Some designers prefer potted cordwood construction for the Cockroft-Walton multiplier section because of space limitations and to reduce problems of surface leakage and tracking.

DESIGN EXAMPLES

In order to illustrate typical successful high-voltage power supply designs as graphically as possible, photographs of actual flight models were obtained. Brief descriptions of the most important, or unusual, features of each power supply accompany the photographs presented. It must be kept in mind that in each case a host of factors besides the electrical requirements entered into the evolution of the final form of the finished unit. These factors include the obvious constraints and requirements such as: specific launch environment (vibration, shock, thermal, pressure), size, weight and efficiency restrictions, time of turn-on, flight duration, required reliability, effects of outgassing and noise on the supply, noise and outgassing cleanliness requirements of other spacecraft experiments, location of supply on the spacecraft, rotation and orbit parameters of the spacecraft, and orbital radiation and charged particle environments. A number of less obvious considerations involving individual component reliability and the extremely difficult multiparameter problem of encapsulation also affected the final results.

An exhaustive discussion of the design examples including all of these factors is beyond the scope of this presentation. More detailed information on the construction, layout of components, choices of components, or encapsulation techniques may be obtained directly from the designers listed in specific examples. Several monographs (see Appendixes and References) that describe general design considerations, construction techniques, and quality control procedures are available.

Design Example 1—~1.5 kV, -10° < T < +50°C*

A well filtered (1-mV noise level) Cockroft-Walton multiplier power supply employs circuit board construction (Figures 37 and 38) and encapsulation with an Emerson and Cuming 1090-SI potting compound (shown prior to encapsulation). This material is filled with glass microballoons and has about the same thermal expansion coefficient as aluminum. It has been found to be very effective in eliminating component breakage due to differential expansion at temperature extremes.

Components employed include Erie Corona-Free Jet Seal high-voltage disc ceramic capacitors, teflon-covered wire used in transformer windings, and 1N649 and 1N4586 high-voltage diodes.

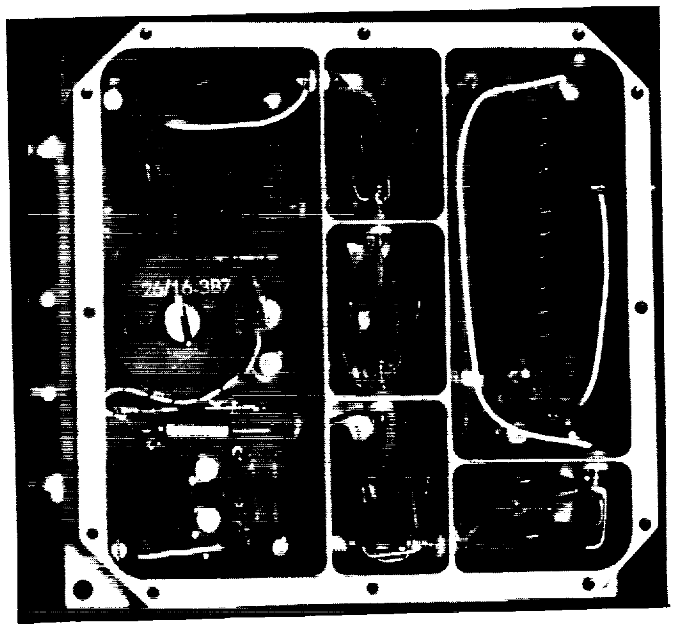


Figure 37. Design Example 1, ~1.5 kV.

A unique feature of the pot core transformer design is the use of partitioned nylon winding bobbins, Figure 39. The integral partitions allow placement of primary and secondary coils side-by-side rather than one on top of the other, eliminating the problem of lead dress. It becomes a simple matter to bring the leads of the primary and secondary, respectively, out opposite sides of the transformer with a partition of nylon completely separating the windings. After completion, the transformers were injection filled with Dow Corning RTV 3140.

*F. C. Hallberg, GSFC, private communication.

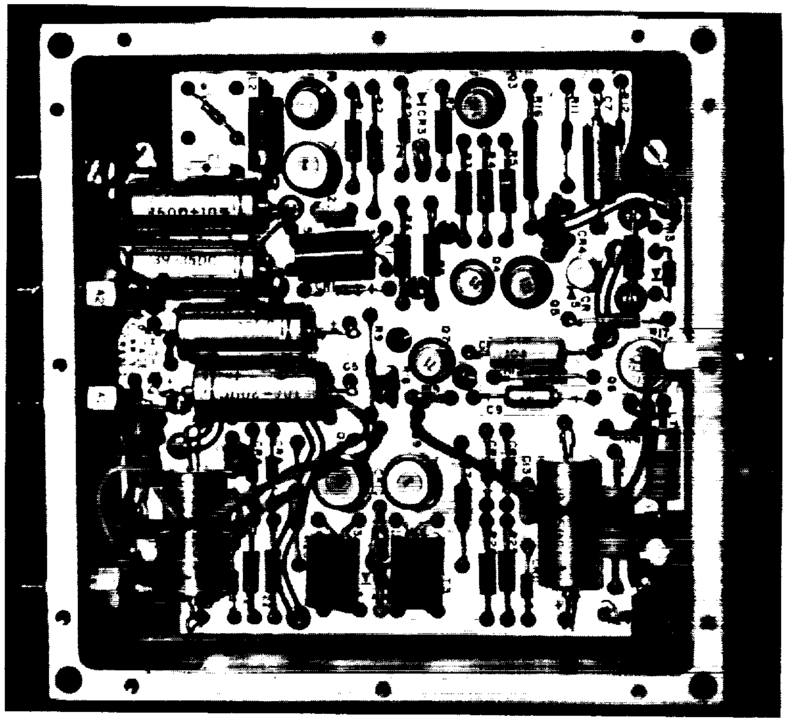


Figure 38. Design Example 1, ~1.5 kV.

Figure 39. Partitioned Winding Bobbin.

Design Example 2—~1.8 kV*

The Cockroft-Walton multiplier section of this supply was built up on a ceramic substrate and conformally coated with Emerson and Cumings EP-3. As shown in Figures 40 and 41, the completed multiplier was assembled inside a gold plated Lexan box. Other than the conformal coating, no encapsulants were used. Components employed include Victoreen MOX-1125 resistors, Microsemiconductor MC002 diodes, and Monolithic Dielectric type 200R23W capacitors.

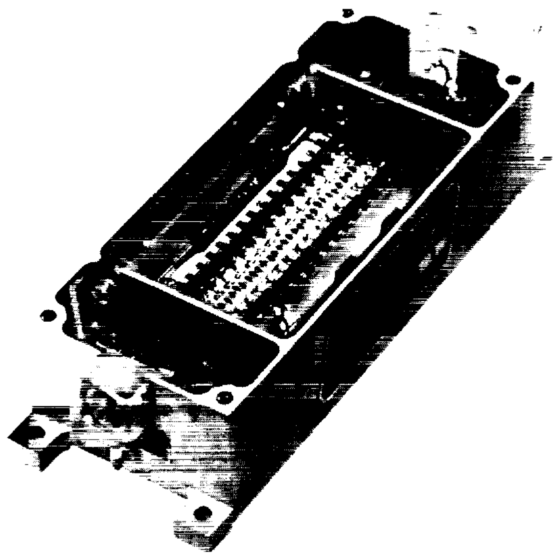


Figure 40. Design Example 2, ~1.8 kV.

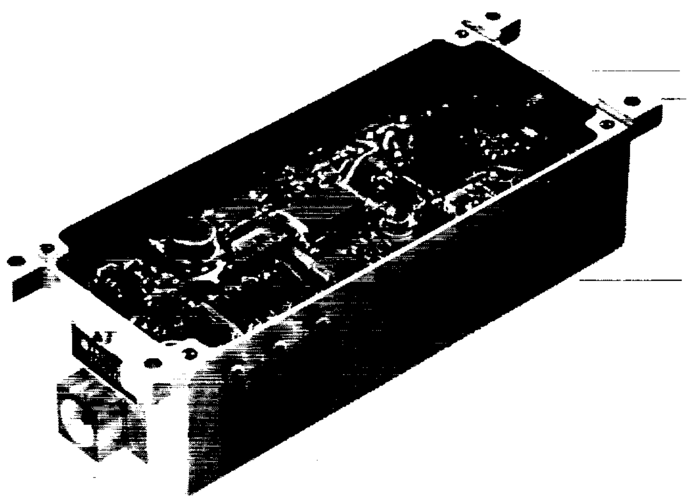


Figure 41. Design Example 2, ~1.8 kV.

*J. H. Trainor, GSFC, private communication.

The 500-volt supply shown in Figure 42 has a similar high-voltage section and illustrates a useful construction technique. Small circuit boards soldered to the mother board are supported against the effects of shock, acceleration, and vibration by an open-cell foam. This material, made by Rogers Foam Corporation, is made of polyester polyurethane and has been used successfully in the space environment.

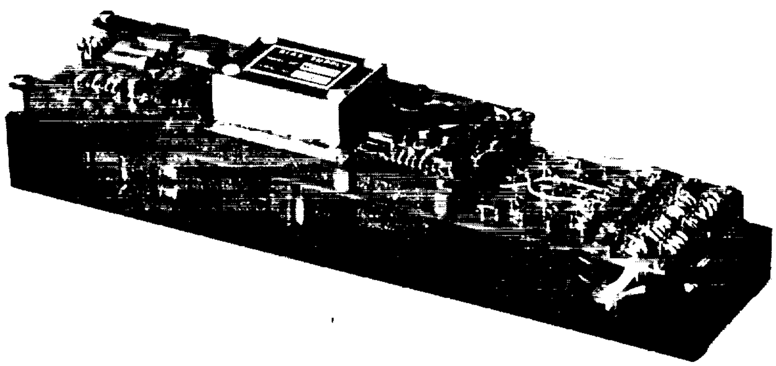


Figure 42. Design Example 2, Use of Open Cell Foam.

Design Example 3—~3.7 kV*

This triangular-shaped supply, Figure 43, developed for the AE spacecraft, generates three voltages selectable by telemetry commands +3700, +3950, and +4200 volts. It features a high-voltage Cockroft-Walton multiplier section built into a gold plated Lexan box potted with DC 93-500. High-voltage leads pass through the box walls inside Lexan dowels. Output leads are Tensolite coaxial cables with H-film insulation. The supply consists of four potted modules: one containing the transformer-multiplier chain, one containing the series current limiter resistors, one containing a voltage reference resistor network, and one containing servo control circuitry. Interbox connections are made with coaxial cable with the shield removed. The multiplier capacitor chain was self supporting prior to potting.

Components employed include Victoreen MOX high voltage resistors, Centralab epoxy coated disk ceramic capacitors, and Semtech type F 25 diodes. The modules are supported by G10 circuit board material etched such that a ground plane is provided beneath the multiplier module. Potting of the modules, including the pot core transformer, was done by pouring at atmospheric pressure and then evacuating to forepump pressures. The transformer was epoxied in place to eliminate bolts and the possibility of attendant trapped gasses.

*J. A. Gillis, GSFC, private communication.

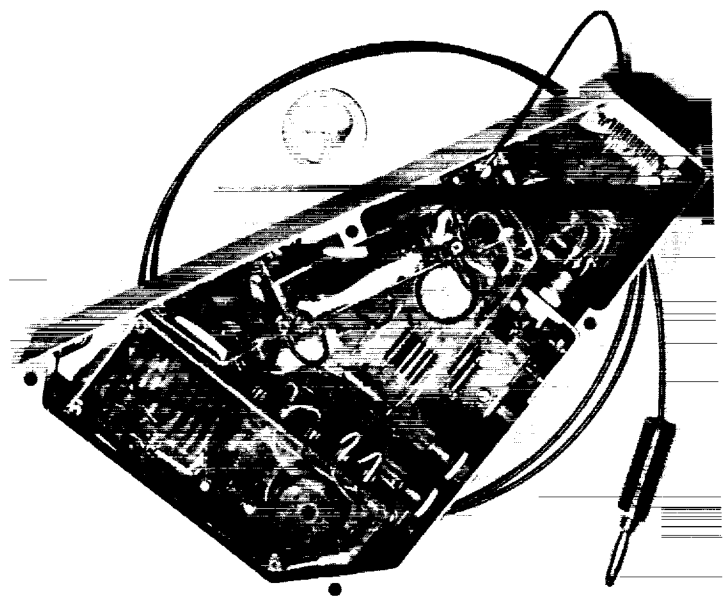


Figure 43. Design Example 3, ~3.7 kV.

Design Example 4—4 kV, 20 μA*

As shown in Figures 44 and 45, this 5-stage Cockroft-Walton supply design incorporated straight-forward circuit board techniques. Components were soldered to an etched G-10 epoxy fiberglass board which was mounted inside a metal box. The components were additionally supported by a conformal coating of Solithane 113. The box was gold plated for thermal control and perforated to allow depressurization to the pressures of orbital altitudes. Teflon tape was applied between layers of windings of the toroidal oscillator transformer, and teflon-covered wire with a 1 kV rating was used for low-voltage circuitry.

Components employed included Centralab blue epoxy coated 6 kV capacitors, Semtech SFM-70 7 kV diodes, and Victoreen solid core, high-voltage resistors. A Reynolds subminiature (0.25 in. O.D.) type 167-2896 10 kV coaxial cable and connector assembly was used to connect the high-voltage supply to the experiment to which it supplied power.

Design Example 5—4 kV†

Figure 46 is a photograph of a unique high-voltage (4-kV) distribution device used to connect several connectors to one power supply. Design requirements were RFI shielding, fast depressurization, absence of outgassing materials, accessibility of the circuit terminations without disruption of experiment integrity, and corona-free operation at pressures as high as

*S. Highley, USNRL, private communication.
†J. T. McChesney, GSFC, private communication.

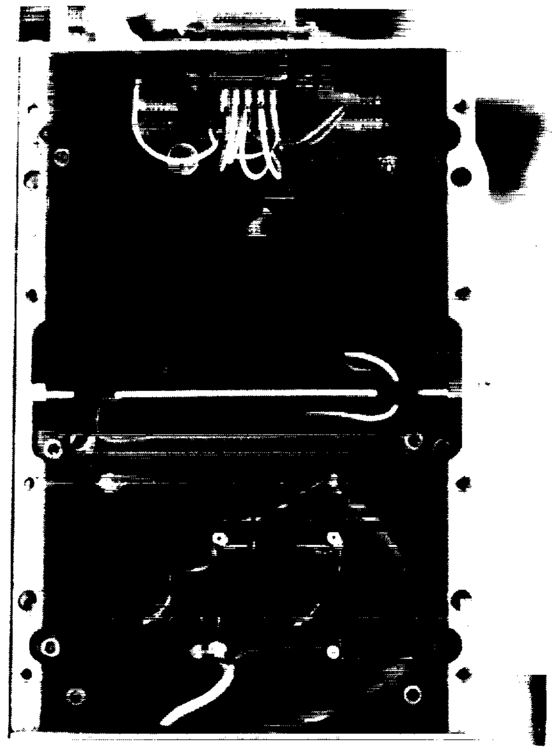


Figure 44. Design Example 4, 4 kV.

6.5×10^{-4} torr. A wire from each detector is soldered into a blind hole in a thick, gold plated, beryllium-copper washer. The washer terminations from several detectors are then clamped in a nut and bolt assembly with hemispherical ends. The assembly is supported inside a metal compartment by corrugated Kel-F stand offs. Kel-F is a fluorocarbon material with excellent electrical properties and good machinability.

Design Example 6—4.5 kV*

The 4500-volt, 10-stage Cockroft-Walton power supply illustrated in Figures 47 and 48 features an unusual construction technique. The high-voltage section is entirely unencapsulated. Instead, spaces for the multiplier components are machined out of blocks of Vespel-1, a tracking resistant polyimide material. Corona paths are confined to seams between the cavities, and surface leakage paths are relatively long. In addition, a resistor-diode current limiting circuit and a current limiting voltage regulator reduce the energy of the discharge should corona develop.

*D. P. Peletier, Johns Hopkins University.-APL, private communication.

Figure 45. Design Example 4, 4 kV.

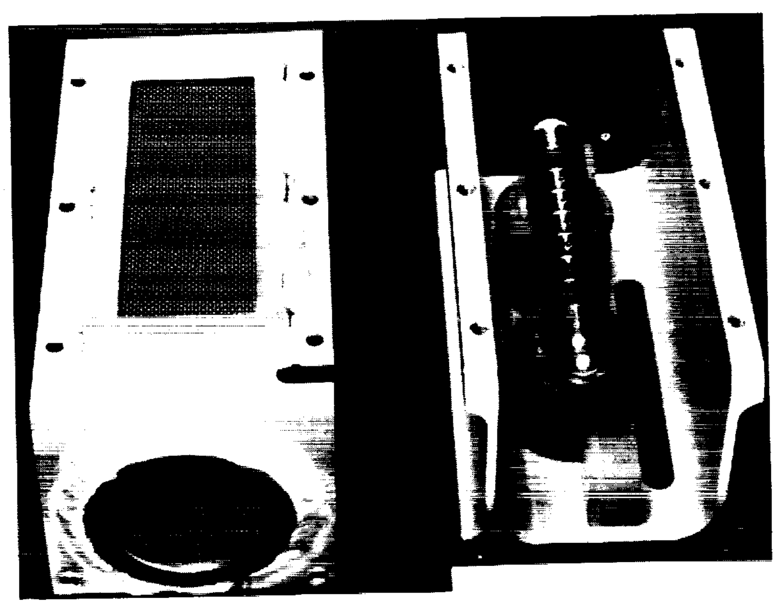


Figure 46. Design Example 5, 4 kV.

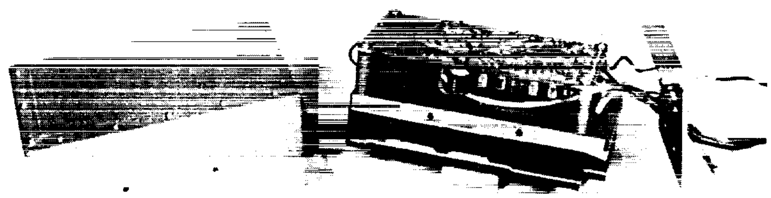


Figure 47. Design Example 6, 4.5 kV.

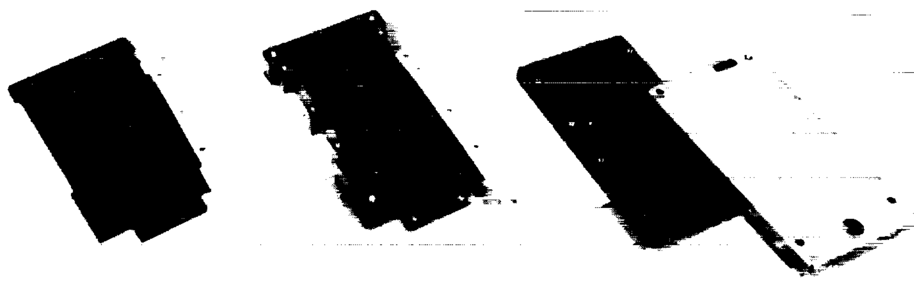


Figure 48. Design Example 6, 4.5 kV.

Components employed include microsemiconductor MH402 diodes, Erie type 808-000-X5RO and 848-026-X5RO capacitors, and Victoreen MOX-400 high-voltage resistors.

Design Example 7—~10 kV*

This power supply shown in Figures 49 and 50, incorporated circuit board construction combined with potting of the Cockroft-Walton diode array and potting of the high-voltage portion of the conductor side of the board as well. The potting compounds employed were GE RTV-615, a two-part clear cuttable compound, and RTV-616 (black) with GE 4153 blue primer, RTV-11 and DC 93-500.

Components employed include Spacetac pot core transformers, G-10 board material, Victoreen MOX1125 high-voltage resistors, Monolithic Dielectric 2-kV ceramic capacitors, and Semicon Corporation #5040J 4-kV diodes.

During construction of several versions of this basic design, breakdowns were observed in voids under the conformally coated high-voltage capacitors. Shimming of these components up 30 mils from the circuit board surface allowed sufficient space to permit flow of the coating material underneath,

*J. Caine, University of Maryland, private communication.

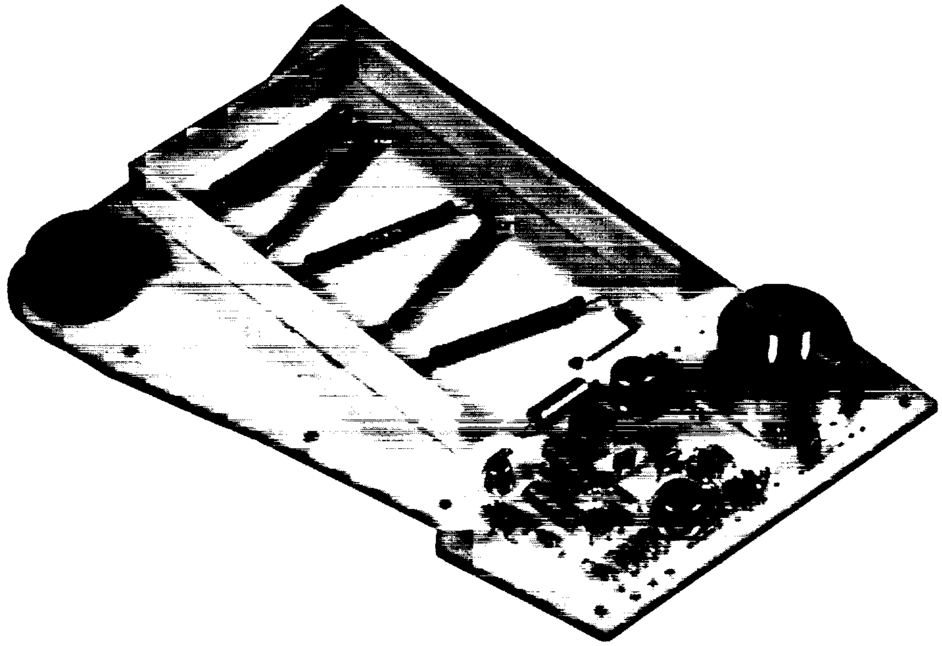


Figure 49. Design Example 7, ~10 kV.

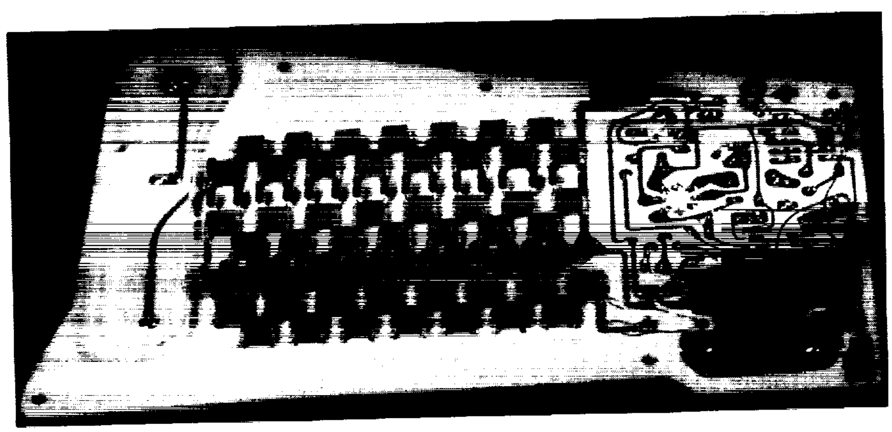


Figure 50. Design Example 7, ~10 kV.

thus eliminating the problem. Another problem, typical of potted modules, was the occurrence of internal discharges of tiny voids with a repetition rate of the order of one per hour per void.

The aluminum cylinder at one end of the supply encases and supports the pot core transformer. The round object at the other end is a special high-voltage connector fabricated of Dupont Vespel. The box over the high-voltage resistors (shown with cover removed) is for physical protection.

Features of this design include small size, light weight, and high efficiency.

Design Example 8—15 kV*

This 10-stage Cockroft-Walton type power supply, Figures 51 and 52, was designed to be located immediately adjacent to the device to which it supplied power, thus eliminating the need for high-voltage cables and connectors. As shown prior to potting in Figure 53, the high-voltage output lead is connected to a terminal located at the center of the circuit board. Lead length was adjusted so that the wire would form a helix through the encapsulant (RTV-615). This construction increases the electrical leakage path along the surface of the wire insulating jacket. The lead connected physically with a corona control electrode through a Kel-F insulated barrier directly above the circuit board.

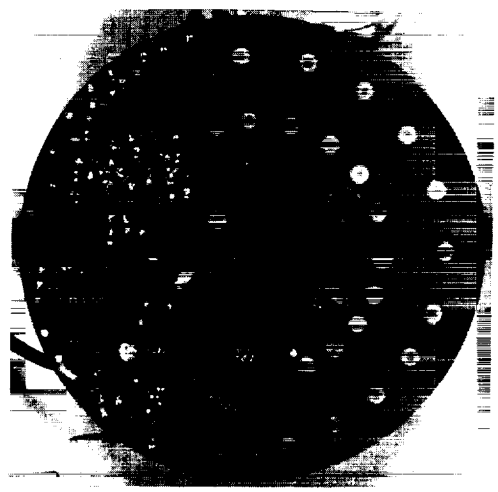


Figure 51. Design Example 8, 15 kV.

After cleaning and inspection, the ceramic capacitors were coated with a 50-50 mixture of Epon 828 and Versamid 140 and overcoated with 93-500. The latter material adhered well to the RTV-615 encapsulant.

All of the high-voltage components were mounted on etched Teflon standoffs in order to keep high potentials well separated from the chassis which is located 0.25 in. from the bottom of the board. Etching was necessary to ensure adhesion to the RTV-615 encapsulant.

The pot core transformer was constructed with the high-voltage winding wound on top of the low-voltage winding. Layers of H-film tape were placed over every third layer of windings. High-voltage lead breakout was made at the extreme perimeter on the opposite side of the core from the primary leads.

*J. L. Westrom, GSFC, private communication.

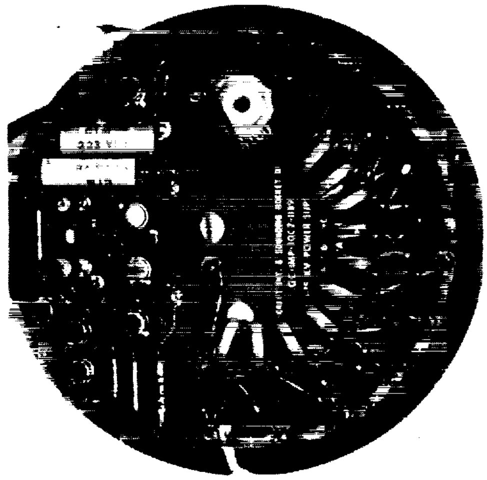


Figure 52. Design Example 8, 15 kV.

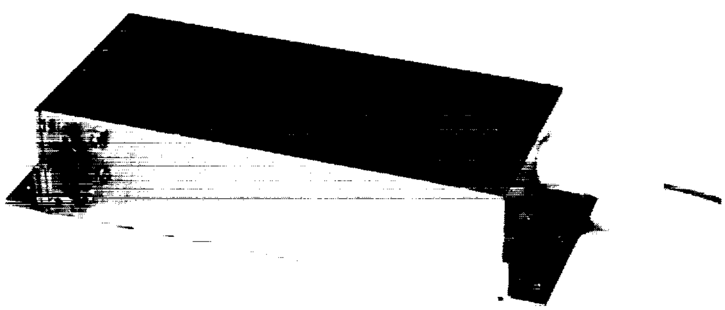


Figure 53. Design Example 9, 25 kV.

Design Example 9—25 kV, -55°C to +100°C*

As shown in Figures 53 and 54, this 25-kV supply was potted as a solid block in a metal box. The multiplier array was self supporting prior to potting with a combination of Sylgard 186 and Sylgard 184. This unusual compound is flexible and performs satisfactorily as an insulator over the required temperature range. The design features field stress reduction at junctures in the array through the use of metal balls welded to the component leads.

*R. G. Reynolds, USNRL, private communication.

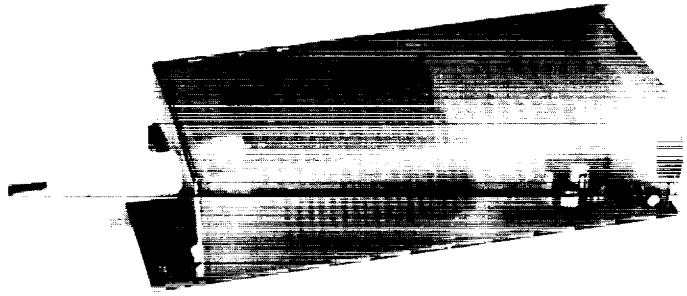


Figure 54. Design Example 9, 25 kV.

Component types employed include Erie 3889-810-X5R0 capacitors with Jet-Seal coating, Vitramon CKR06BX capacitors, Semtech SFM-70 7-kV diodes, Caddock MG721 series high-voltage resistors, and Daburn etched Teflon shielded cable.

Design Example 10—~100 kV, Sounding Rocket Experiment*

The 100-kV, 5-μA supply shown in Figures 55 through 58 was designed as a Cockroft-Walton device contained within a vessel pressurized to 15 psig with SF_6. The concept of employing only ceramics, metals, and SF_6 in the construction wherever possible follows the design practice developed over many years for construction of Van de Graaf generators. No encapsulants were employed.

The stack of fins visible in Figures 56 and 57 separate sandwich pairs of uncoated capacitor wafers, Sprague type 41C-0Z5-C23C. Metallic lead wafer separators were employed to relieve local stress concentrations in the ceramic capacitor dielectrics.

A 150-megohm series limiting resistance consisting of ten 15-megohm Caddock MG 689 film resistors was employed. Other components employed in this high-voltage supply were a Feroxcube type 4229 PLOO/3BZ pot core transformer, 40 Semtech type 1N5184 diodes, and a 10^{11} Ω voltage sampling resistance consisting of twenty 5×10^9 Ω RPC type BBMW resistors.

A unique feature of this supply design was the shape of the high-voltage electrodes. The structure is that of two flat plates forming a parallel plate capacitor separated by the Cockroft-Walton diode array. That is, the whole upper end of the cylindrical container is a conductor at high potential. As can be seen by referring to Table 1, this results in lower electric field stresses than would occur, for example, between a small electrode (connector) and the base plate.

*F. Scherb, University of Iowa, private communication.

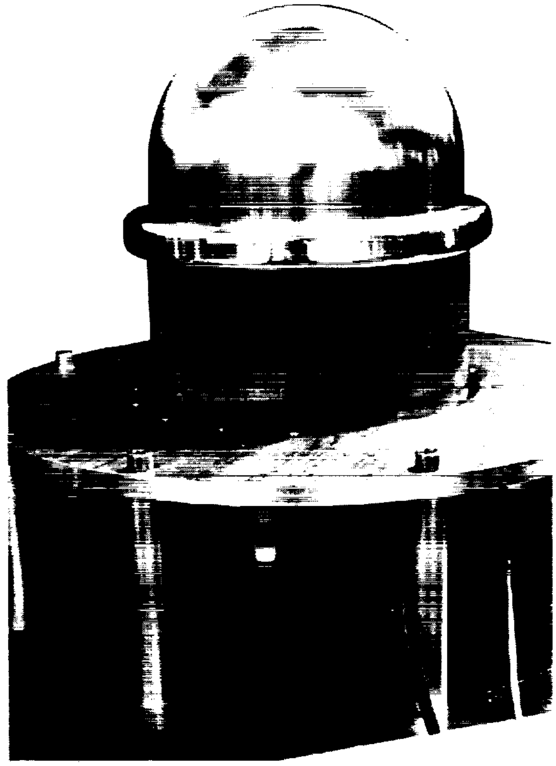


Figure 55. Design Example 10, ~100 kV.

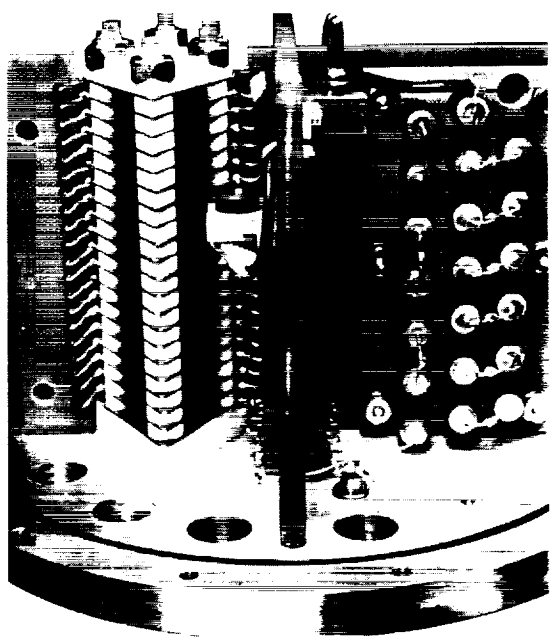


Figure 56. Design Example 10, ~100 kV.

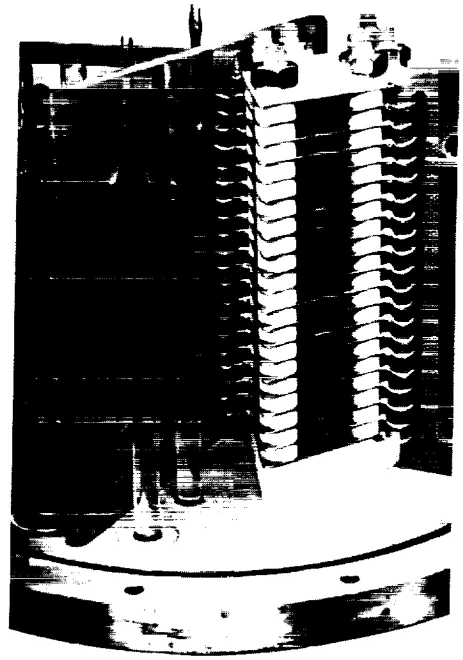


Figure 57. Design Example 10, ~100 kV.

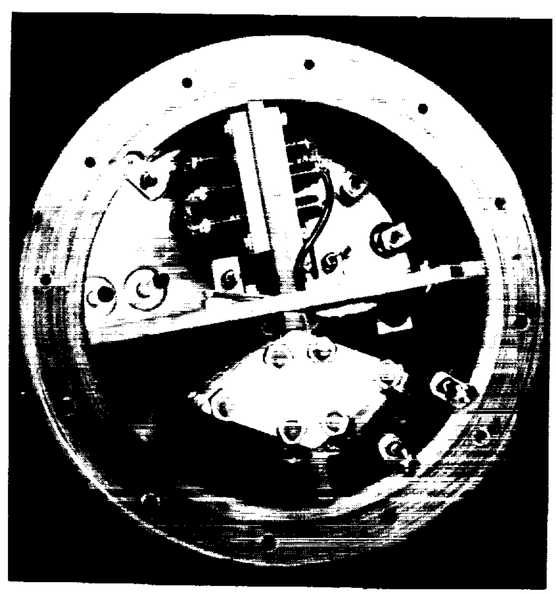


Figure 58. Design Example 10, ~100 kV.

ACKNOWLEDGMENTS

We would like to thank all the contributors who have provided us with detailed information on their successful methods for avoiding electrical breakdown in spacecraft high-voltage systems. These methods include specific techniques, materials, and components which have been used and developed at various test facilities.

Special thanks are given to John Westrom and Dr. Ben Seidenberg of Goddard Space Flight Center. Mr. Westrom contributed much information on the techniques and details of electronic and electrical circuit design. Dr. Seidenberg assisted us greatly with the preparation of the section on encapsulants.

Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, Maryland December 1974
039-23-01-01-51

REFERENCES

1. Stern, J.E., and K.E. Mercy, "A Study of Voltage Breakdown in Spacecraft Systems from Test and Flight Experience," Proceedings of the Second Workshop in Electronic Equipment at Low Air Pressure, Tech. Memorandum 33-447, Jet Propulsion Laboratory, March 1969.

2. Meek, J. M., and J. D. Craggs, *Electrical Breakdown of Gases*, Oxford, 1953.

3. Krebs, W. H., and A. C. Reed, "Low Pressure Electrical Discharge Studies," STL/TR-59-0000-09931, Air Force Contract 04 (647)-309, December 1959.

4. Von Engel, A., *Ionized Gases*, Oxford, 1965.

5. Dunbar, W. E., "Corona Onset Voltages of Insulated and Bare Electrodes in Rarefied Air and Other Gases," AF APL-TR-65-122, The Boeing Co., June 1966.

6. *U.S. Standard Atmosphere 1962*, NASA, USAF, and USWB, 1962.

7. Bowers, A., and P. G. Cath, "The Maximum Electrical Field Strength for Several Simple Electrode Configurations," *Philips Tech Review*, 6, 1941, p. 270.

8. Alpert, D., D. A. Lee, E. M. Lyman, and E. E. Tomaschke, "Initiation of Electrical Breakdown in Ultra High Vacuum," *Proceedings of the International Symposium on Insulation of High Voltages in Vacuum*, M.I.T., October 1964.

9. Anderson, H. W., "Effect of Total Voltage on Breakdown in a Vacuum," *Electrical Engineering*, 54, 1935, p. 1315.

10. Trump, J. G., and R. J. Van de Graaf, "The Insulation of High Voltages in Vacuum," *J. Appl. Phys.*, 18, 1947, p. 327.

11. Inge, L., and A. Walther, *Arch. Elektrotech.*, 26, 1932, p. 409.

12. Sprengling, G. R., and S. J. Ponemone, "Volume Resistance Behavior of Laminated Circuit Boards under High Humidity Conditions," *10th Proceedings of the Electrical Insulation Conference*, 1971, p. 161.

13. Sprengling, G. R., "Effects of Humidity on Polymer Surfaces," *Annual Report of the Conference on Electrical Insulation and Dielectric Phenomena 1971*, 1971, p. 83.

14. Milek, J. T., "EPIC (Electronic Properties Information Center)" AFML-RTD-AFSE, AF 33 (615) - 1235, Sulfur Hexafluoride Data Sheets DS-140, October 1964.

15. Clark, F. M., "Insulating Materials for Design and Engineering Practice," John Wiley, 1962, p. 699.

16. Sacher, E., "Resistivities of Curing Epoxy Systems II. Bisphenal-A Diglycidyl Ether/Polymide," *Annual Report of the Conference on Electrical Insulation and Dielectric Phenomena 1971*, 1971, p. 249.

17. Rogers, E. C., and D. J. Skipper, "Gaseous Discharge Phenomena in High Voltage D.C. Cable Dielectrics," *Proc. of the Institution of Electrical Engineers*, **107**, Part A, No. 33, June 1960, p. 241.

18. Dosser, D. M., "Electrical Shorts," 3M Company.

19. Lee, E. A. R., "Laminated Materials for Printed Circuit Boards," *Electronics and Power*, November 1972, p. 392.

20. Scialdone, J. J., "The Outgassing and Pressure in a Spacecraft," *Proc. of Institute of Environ. Sciences*, Mt. Prospect, Ill., 1974.

21. Scialdone, J. J., "Internal Pressures of a Spacecraft or Other Systems of Compartments Connected in Various Ways and Including Outgassing Materials in a Time Varying Pressure Environment," NASA TM X-63869, August 1969.

22. Everhart, E., and P. Lorrain, "The Cockroft-Walton Voltage Multiplier Circuit," *Rev. Scientific Instrum.*, **24**, 1953, p. 221.

23. Rumble, G. P., "A Universal Voltage-Multiplier Circuit," *QST*, March 1973, p. 48.

24. Weiner, M. W., "The Cockroft-Walton Voltage Multipliers with an Arbitrary Number of Stages," *Rev. of Scientific Instrum.*, **40**, February 1969, p. 330.

25. Mostov, P. M., L. J. Neuringer, and D. S. Riguiy, "Optimum Capacitor Charging Efficiency for Space Systems," *Proc. of the IRE*, May 1961, p. 941.

APPENDIX 1

HIGH VOLTAGE ELECTRONIC PACKAGING
FLIGHT EQUIPMENT

DESIGN REQUIREMENTS

CODE IDENT NO. 23835

DES. REQ. DM505139 REV. A

ISSUE DATE 24 November 1971

SUPERSEDING

DATED

HIGH VOLTAGE ELECTRONIC PACKAGING
FLIGHT EQUIPMENT

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1. SCOPE

1.1 Scope. This document covers the design requirements for the protection of high voltage flight equipment from damage due to arcing or corona breakdown.

1.2 Applicability. The high voltage protection requirements described herein are to be applied to packaging design and testing of electronic equipment operating above the voltage minimum as specified in 3.2.1.

1.3 Objectives. The main objective of high voltage electronic packaging requirements described herein is to assure that the electronic equipment employing high voltages will survive and operate without damage due to an intentional or inadvertent turn-on while in the critical pressure area during testing, or a high Earth altitudes, other planetary atmospheres, or the vacuum of space. Demonstration by actual testing is required to demonstrate that the high voltage electronic equipment will survive operation in this environment. Another objective is to qualify details of design such as:

a. Design concept.
b. Adequacy of interconnections.
c. Effectiveness of protective devices.
d. Effect on other subsystems.
e. Quality of workmanship.

Voltage breakdown considerations not included in this document are break downs at frequencies above 1.0 GHz in cavities or wave guides in vacuum due to secondary emission (multi-pacting) or other effects not requiring ionization of a gas for initiation.

1.4 Classes of electronic equipment. Electronic equipment will be classified as Class 1 or Class 2 in accordance with 1.4.1 and 1.4.2.

1.4.1 Class 1 equipment. Class 1 equipment will be designed to operate to specification requirements throughout its operational lifetime without voltage breakdown (arcing or corona) present at any pressure, unless such arcing or corona is a proper functional requirement (e.g., spark gaps).

1.4.2 Class 2 equipment. Class 2 equipment will be designed so that any voltage breakdown which may appear during operation at any pressure will not cause damage to its internal components or to other external equipment, or degrade the mission to an unacceptable limit. During the time that voltage breakdown is occurring, operation to specification requirements is not required. In applications where insulation to prevent corona or arcing cannot be used because of interference with the proper functioning of the unit (e.g., plasma detector screens), protective devices such as horn or ring gaps will be used to reduce the possibility of arcing or corona occurring in the unit. Power supply output may be self limiting to prevent damage due to arcing or corona.

2. APPLICABLE DOCUMENTS

2.1 The following documents, of the issue specified in the contractual instrument, form a part of this document to the extent specified herein.

SPECIFICATIONS

Jet Propulsion Laboratory

FS500443	Process Specification, Transformer and and Inductors, Electronic Packaging, General Specification for
FS505284	Process Specification, Printed Wiring Boards and Assemblies, Double Sided, Solder Plated, Detail Specification for
FS505789	Process Specification, Fabrication of Multilayer Printed Circuit System with Plated-Through Holes, Detail Specification for
FS506079	Process Specification, Printed Wiring Boards and Assembly, Detail Specification for

Military

MIL-T-27C	Transformers and Inductors (Audio, Power, and High Power), General Specification for

STANDARD

Military

MIL-STD-202C	Military Standard, Test Methods for Electronic and Electrical Component Parts

DRAWINGS

Jet Propulsion Laboratory

ST10591	Terminal, Electrical, Slotted, Swage Mount
ST11308	Terminal, Electrical, Slotted, Swage Mount

(Copies of specifications, standards, procedures, drawings, and publications required by suppliers in connection with specific procurement functions should be obtained from the procuring activity or as directed by such activity.)

3. REQUIREMENTS

3.1 Conflicting requirements. In case of conflict between the requirements of this document and the requirements of any document referenced herein, this document shall have precedence.

3.2 General. All flight electronic equipment to be exposed to the critical pressure region (refer to 6.1.3) and employing voltages above the minimum specified in 3.2.1 (a function of frequency) shall comply with the requirements of this document. This requirement is in addition to the basic electronic packaging requirements of the applicable design requirement and functional requirement documents.

3.2.1 High voltage limits. The requirements of this document shall be mandatory for flight electronic equipment with circuit conductors having instantaneous voltages (with respect to other circuit conductors, to the common ground, or to the subchassis) in excess of 250 volts peak. This limit is applicable to frequencies from d.c. to 60 Hz, and shall be reduced in accordance with Figure 1 for frequencies above 60 Hz.

At voltages lower than that specified in 3.2.1, compliance may be desirable for one or more of the following reasons:

a. The conductive plasmas generated by a corona or arc, or other mechanisms such as passage of the vehicle through low pressure gaseous environments, can drift across bare conductors carrying much lower voltages (e.g. 24 volts), initiating arcing in these circuits also.

b. The theoretical breakdown voltage minimum of 270 volts peak is for air; other gases, especially the noble ones, even in trace quantities, can cause breakdown to occur at much lower voltages.

c. Other conditions being the same, reduction of large voltage gradients, by suitable gradient control techniques, will markedly improve the long term reliability of high voltage circuits.

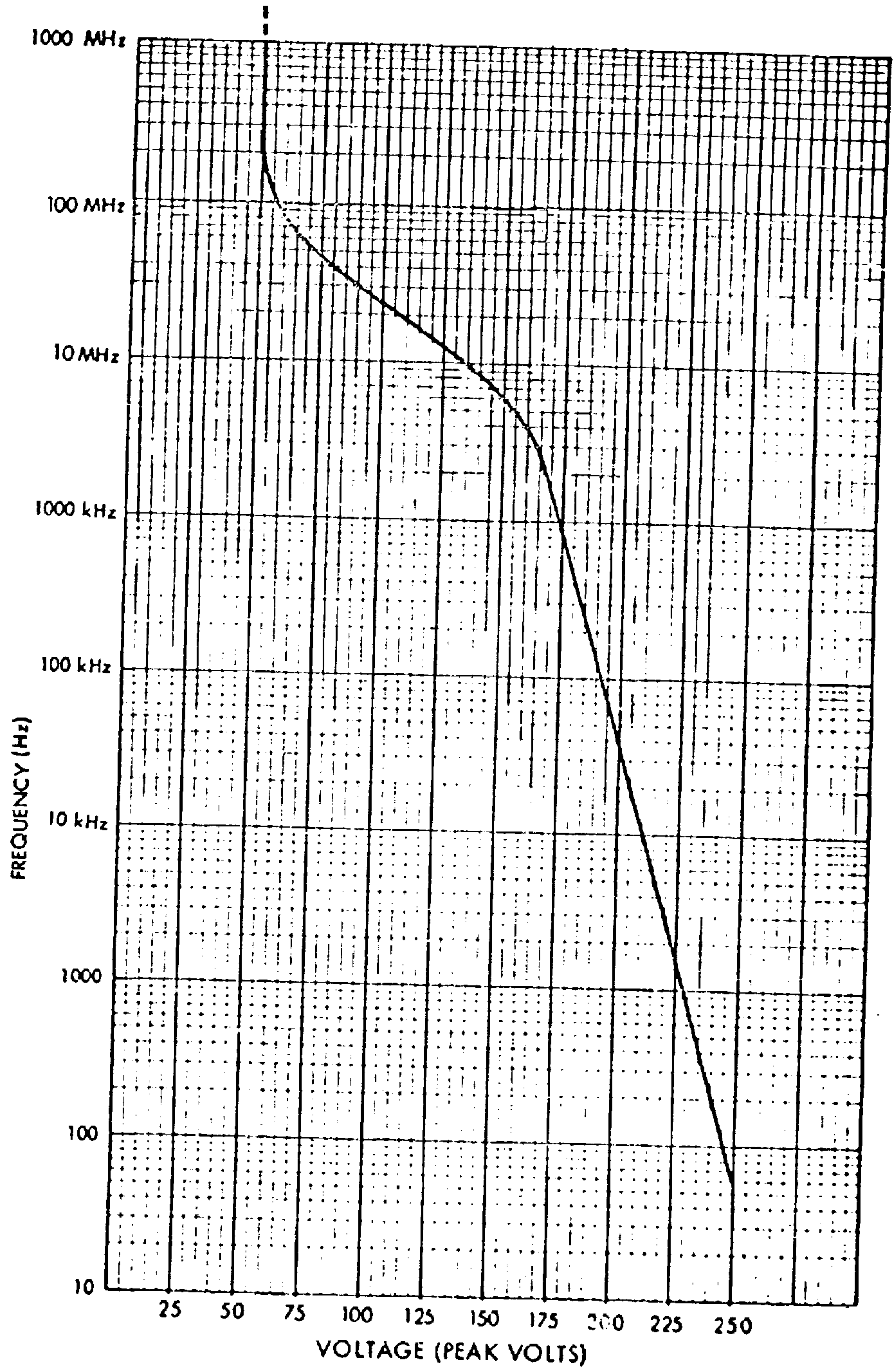


Figure 1. Lower Voltage Breakdown Limit versus Frequency for Earth Atmosphere

3.2.2 Frequency range. The range of frequencies governed by this document shall be from d.c. to 10 GHz for sinusoidal waveforms, or from d.c. to 1.0 GHz for all other waveforms.

3.3 Circuit geometry of printed wiring and terminal boards. Printed wiring (etched circuit) conductors shall not be used in circuits with voltages between conductors in excess of 1000 volts peak unless special precautions are taken to reduce the voltage gradients along the conductor edges. Printed wiring boards and assemblies shall be in conformance to the requirements of JPL Specification FS505284, FS505789, or FS506079.

Terminal boards, using swaged terminals per JPL Specification FS505284 or FS506079, using discrete components and solid bus wire for interconnection, or similar packaging techniques where voltage gradient control can be demonstrated or calculated, shall be used for high voltage circuits operating at voltages above 1000 volts peak.

Terminal pads shall not be used under swaged terminals in circuits with voltages above 1000 v peak. Printed wiring and terminal boards used in high voltage circuits shall meet the requirements of 3.3.1 through 3.3.12.

3.3.1 Separation of high voltage circuits. Circuits employing high voltage shall be physically separated from low voltage circuits with a minimum common boundary when located on the same printed wiring or terminal board, as shown on Figure 2. The minimum distance between high and low voltage conductors shall be as given in 3.3.3 and 3.3.4.

3.3.2 Low voltage circuit protection. A ground bus shall be located between high and low voltage circuitry to prevent possible creepage currents or arcs causing interference or damage with the low voltage circuits as shown on Figure 2. Where the high voltage circuit is physically separate from the low voltage circuit board, a ground bus around the perimeter of the high voltage board shall be used to prevent a possible arcing to the low voltage circuits. Where high voltage exists on both sides of the printed wiring or terminal board, the ground bus shall be on both sides, preferably superimposed one above the other as shown on Figure 3. This ground bus should be wider than regular conductors to provide a lower impedance return path for an arc. A ground bus shall be used in each layer of a multilayer circuit to isolate the high voltage circuits from the low voltage circuits. In selected areas, the ground buses may be staggered instead of superimposed to allow conductors to pass between the high and low voltage areas by transferring from one layer to an adjacent one; or the ground bus on a given layer may be interrupted to allow passage of such conductors. The connection to the ground point for this bus shall be so that the currents from a possible arc will not be coupled into the ground returns of any other circuits.

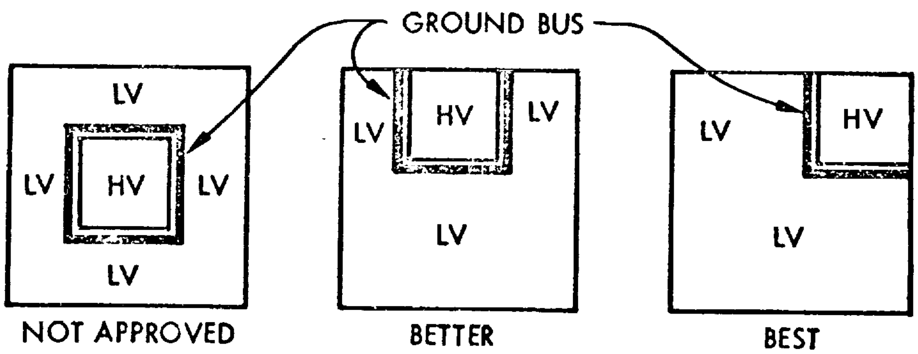


Figure 2. Common Boundary, HV & LV Circuits

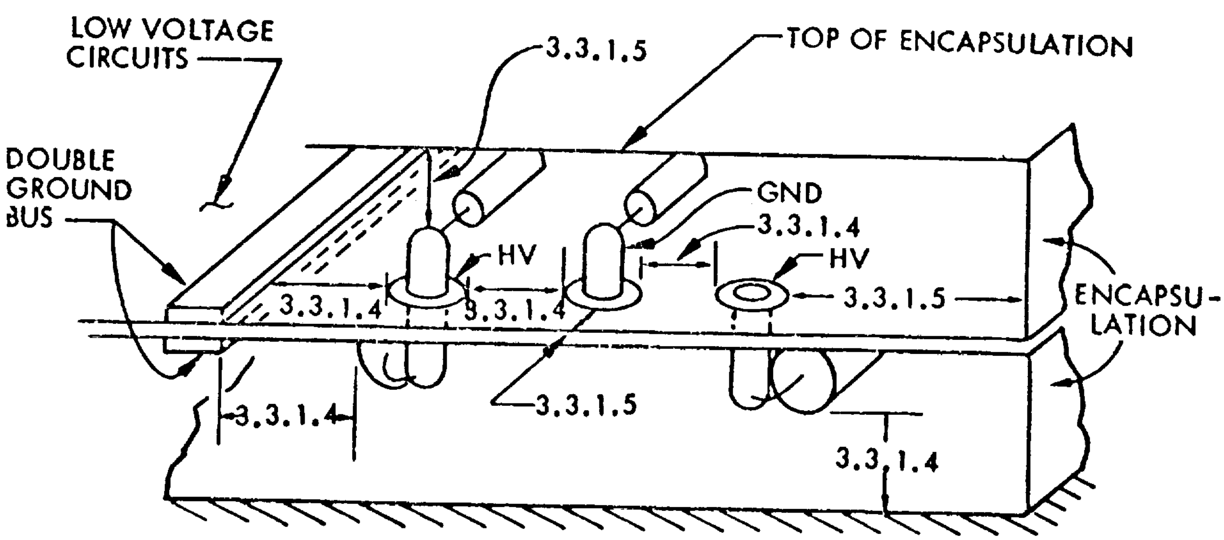


Figure 3. Required Separation of High Voltage Parts

3.3.3 Measurement of conductor separation. The distance between conductors, terminals, or other metallic surfaces with high voltages between them shall be measured in a straight line from the points of closest approach, including worst tolerance buildup, and disregarding any intervening insulation materials. The linear voltage gradient is computed in accordance with 3.3.10.

3.3.4 Conductor spacing. The minimum separation of conductors carrying voltages in accordance with 3.2.1 on the same side of the printed wiring or terminal board shall be as given by the empirical equation:

$$d = 0.250\sqrt{V}$$

(where d is in inches and V is the maximum peak voltage difference between the conductors in kilovolts.)
The minimum separation shall be 0.125 inch. Distances shall be measured along the surface between the conductors and shall be the minimum distance possible. Layout of the high voltage circuitry should consider gradient reduction by placing conductors in order of decreasing voltages, if such locations do not cause adverse effects on the performance of the circuit.

3.3.5 Spacing from edge. The minimum distance of the conductors from the edge of the printed wiring or terminal board shall be 1.5 times the value obtained from the equation in 3.3.4, as shown on Figure 3.

3.3.6 Sharp points. Circuit conductors, electronic parts, and mechanical parts either in the high voltage circuit, grounded, or insulated electrically but located at a distance that is less than twice the distance specified in 3.3.4 from the high voltage conductors, shall be designed or laid out in a manner that will avoid sharp points, corners, and abrupt changes in dimensions. Smooth curves rather than sharp corners shall be used for changes in direction of all printed wiring conductors. Solder fillets shall be smooth.

3.3.7 Solder terminals. Swaged terminals shall be in accordance with the requirements of JPL Specifications FS506079 and FS505284, and the requirements of this document. Preferred terminals for voltages shall be per JPL Drawing ST10591 or ST11308. For applications which require larger terminals, the bifurcated terminals specified in JPL Specification FS505824 shall be permitted, subject to the following additional requirements of this paragraph and Figure 4. Ends of part leads shall be flush with the edge of the terminal to 0.030 shorter. After part leads are installed, the terminals at voltages above 1.0 kv shall have any excess length of the bifurcation trimmed off as shown on Figure 4. A smooth solder joint shall be made to enclose all cut ends of leads and trimmed bifurcations to reduce the voltage gradient. A smooth solder ball or other conductive material shown on Figure 4 is allowable for high voltage terminals. For circuits above 1.0 kv, the terminals shall have a hemispherical conducting cap to reduce the voltage gradient at the edge of the swage as shown on Figure 4. Use of solder terminals should be kept to a minimum in high voltage circuits.

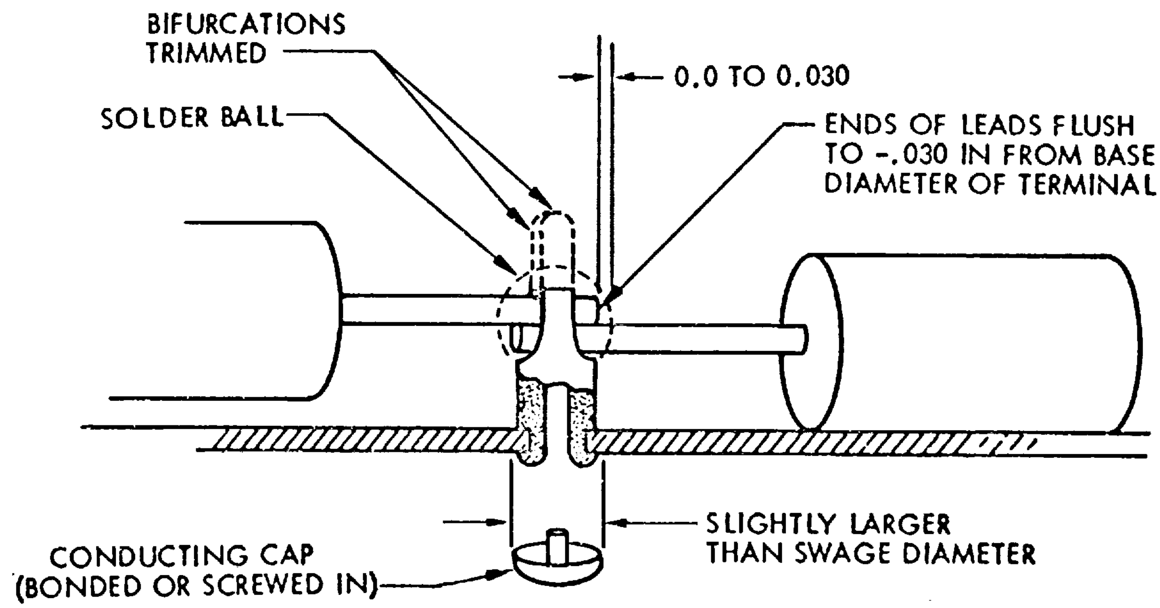


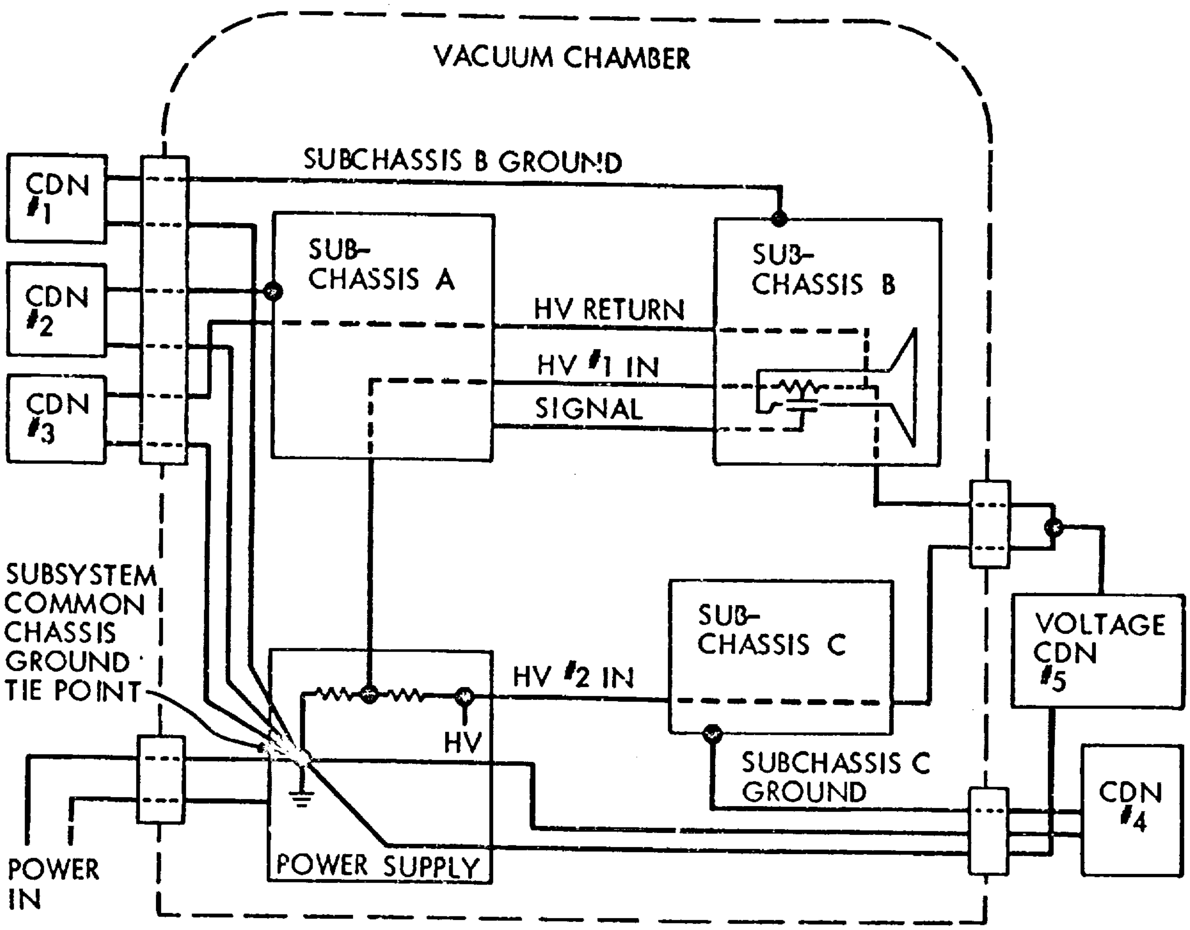
Figure 4. Solder Terminals

3.3.8 Grounding. Chassis ground leads shall be separate from signal and power return leads to prevent corona or arc currents from adversely affecting or damaging other circuits. Provisions shall be made so that corona detection networks may be inserted in series with chassis grounding leads during subsystem tests as shown on Figure 5. Ground lead continuity is through the corona detection networks, which have a very low impedance at low frequencies. Ground leads shall be such that ground loops are not permitted.

3.3.9 Grounded shield for ac circuits. High voltage ac circuits, which are encapsulated per 3.4, shall be enclosed by a conducting ground shield to prevent the occurrence of corona at the surface of the encapsulant when operating in the critical pressure region. Special precautions shall be taken to prevent the inclusion of any bubbles or voids between the shield and the high voltage conductors. This shielding requirement may be waived if it can be demonstrated that the high voltage circuitry will operate without corona or arcing while at the minimum dielectric strength in the critical pressure region for a period of time to allow all enclosed volumes to vent down to this pressure. The shielding requirement may also be waived if the equipment is not intended to function in a low dielectric strength gaseous environment (e.g., Lunar Lander).

3.3.10 Voltage gradient limits. The thickness of insulation shall be so that the maximum voltage gradient will be 40 volts/mil thickness, or ten percent of the actual breakdown voltage for the thickness of insulation used in the design, whichever voltage stress is smaller. This is the linear gradient, calculated by dividing the peak voltage by the distance in mils. If the geometry is one in which calculation of the maximum gradient is possible, then the maximum stress allowable shall be 100 volts/mil, or 25 percent of the actual breakdown voltage for the same thickness, whichever is smaller.

3.3.11 High voltage pulse circuits. Minimum separation as specified in 3.3.4 of conductors carrying pulses may be reduced by multiplying factor $\frac{t}{t + 0.8}$ (where t is the pulse width in microseconds). The pulse duty cycle shall be less than five percent for this reduction to apply.



NOTES.

1. CDN = CORONA DETECTION NETWORK (SEE FIGURE 3).
2. CDN 1, 2, 4 MONITOR POSSIBLE CORONA CURRENTS FROM HIGH VOLTAGE LINES TO CORRESPONDING SUBCHASSIS. CDN 3 MONITORS POSSIBLE CORONA CURRENTS BETWEEN HV #1 CONDUCTOR AND RETURN.
3. IN CASES WHERE IMPEDANCE IN RETURN OR CDN ADVERSELY AFFECTS SUBSYSTEM OPERATION, VOLTAGE TYPE (CDN #5) MAY BE CONNECTED TO HV LEAD (#2) AS SHOWN.
4. ONE CDN WITH GROUNDING SWITCH COULD BE USED IN PLACE OF CDN 1, 2, 3, 4.

Figure 5. Insertion of Corona Detection Networks in Subsystem Ground Returns

3.3.12 Enclosures. Enclosures which are not hermetically sealed shall be vented directly to the ambient vacuum of space. The total area of vent opening shall allow the pressure in the enclosed volume to bleed down to 3×10^{-3} torr in 60 seconds or less, when the pressure is reduced from ambient sea level to 10^{-5} torr in six seconds or less. The pressure referred to includes both residual air and outgassing in the enclosure. Experience has shown that venting of enclosures may not be adequate to reduce the pressure below the critical region. Consequently, high voltage circuits contained in the enclosure shall be assumed to be exposed to the lower end of the critical pressure region, e.g. 10^{-3} to 5×10^{-4} torr, unless otherwise demonstrated by suitable tests.

Hermetically sealed enclosures shall be acceptable if the product of the measured leak rate and the mission time is one in which the resultant pressure in the enclosure is above the critical pressure region.

3.4 High voltage insulation materials. High voltage insulation materials shall have the following requirements.

3.4.1 Dielectric strength. Insulating materials having the higher dielectric strengths shall be used in high voltage applications when other properties or characteristics pertinent to the application are similar. Materials with dielectric strengths of less than 400 volts/mil measured between parallel plates at the thickness required should be avoided.

3.4.2 Dielectric constant. Insulating materials with low dielectric constants shall be selected for insulation of ac voltages. Where two different insulating materials are in contact, they should be selected so that the difference in their dielectric constants is minimal. Materials with dielectric greater than five shall be avoided.

3.4.3 Air dielectric strength. For purposes of equipment design in accordance with this document, air shall be assumed to have a zero dielectric strength in the critical pressure region.

3.4.4 High frequency applications. Insulation materials selected for use in the high frequency (nominally above 1.0 MHz) applications shall have the dielectric constants and dielectric losses small enough so that blistering, delamination, or other internal damage cause by internal heating will not occur during normal operation.

3.4.5 Foams. Expanded or syntactic foam materials, or materials that are porous, shall not be used for high voltage insulation applications.

3.4.6 Low arc resistant materials. Organic insulating materials, which have a tendency to sustain arcing under any pressure condition or which deteriorate or outgas under arcing conditions, shall not be used in contact with bare conductors emerging from the insulating material and exposed to the ambient pressure. Inorganic insulating materials, which do not sustain arcing, shall be used to provide the interface of an emerging bare conductor from the embedment or conformal coating as shown on Figure 6.

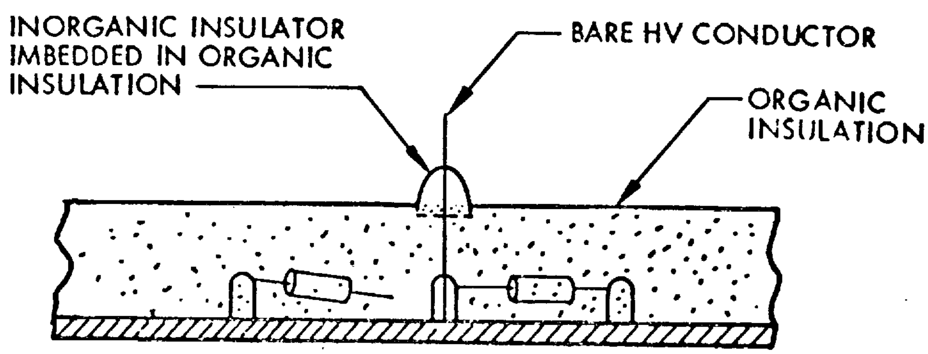


Figure 6. Inorganic Insulation Material

3.4.7 Filled materials. Insulation, which employs fillers or discrete materials mixed throughout its volume, shall have a dielectric strength design limit within the requirements of 3.3.10 computed for that material of the mixture with the lowest dielectric strength.

3.4.8 Insulation coating. All exposed conductors carrying high voltages shall be conformally coated or embedded in a plastic material in conformance with this document. Conductors, which must be exposed to the ambient pressure for proper functioning (e.g., spark gaps), shall be exempt from this requirement.

3.4.9 Adhesion of polymeric materials. Selection of polymeric insulation materials and preparation of solid surfaces in contact with such materials shall assure proper adhesion of the polymeric materials to eliminate creepage paths between conductors.

3.4.10 Removal of absorbed gas. Insulation materials in liquid form prior to polymerization shall be exposed to a vacuum sufficient to remove entrapped gas. Suitable precautions shall be taken to prevent re-entry and trapping of air into the insulation material prior to use and during application. Pouring of insulation material into mold while both items are under vacuum will prevent air entrapment.

3.5 Electronic parts for high voltage applications. In addition to requirements imposed by project parts documents, the electronic parts used in high voltage circuits shall meet the following requirements.

3.5.1 High voltage transformers and inductors. Transformers and inductors shall meet the requirements of JPL Specification FS500443, and 3.5.1.1 through 3.5.1.5 herein.

3.5.1.1 Maximum voltage between turns. The thickness of the enameled magnet wire insulation coat and winding technique shall be so that the maximum possible voltage between any two adjacent wires in a winding shall be accordance with 3.3.10, and in no case larger than 40 volts peak. Voltages at terminations of windings and between wires in excess of this value shall employ additional insulation in accordance with 3.3.10. In high voltage pulse transformers with pulse widths of 10 μsec or less, the allowable voltage limit between wires may be 200 volts peak.

3.5.1.2 Core connection. Electrically conductive cores electrically insulated from the mounting base of the transformer or inductor shall have an auxiliary lead brought out to facilitate hypot tests between the core and the windings to test core insulation integrity (if there is no internal connection between a winding and the core). Cores fabricated from high permeability magnetic materials and encased in plastic matter by the manufacturer shall be exempt from this requirement, provided that the plastic material is in accordance with 3.4 and is sufficiently transparent to allow measurement of the minimum thickness of insulation separating the core from the winding. Cores encased with metallic covers and covered with insulation material also shall be exempt provided that the insulating material is in accordance with 3.4, and the low voltage winding (primary) is between the high voltage windings and the core.

3.5.1.3 Interwinding insulation. Insulation between windings shall be in accordance with 3.4 and shall be capable of withstanding, without damage, the tests described.

3.5.1.4 Winding embedment. Windings shall be impregnated and then encapsulated or shall be embedded with suitable materials and techniques in accordance with 3.4, so that all wires are securely anchored and no pockets or voids occur.

3.5.1.5 Winding terminations. Windings terminated into insulated lead wires shall be embedded in accordance with 3.5.1.4 and the requirements of this paragraph. Terminals employed for termination of transformer or inductor windings shall meet the requirements of 3.3.7, prior to conformal coating or encapsulating in accordance with 3.4. The conformal or encapsulant material shall be compatible with the lead wire insulation and achieve a thorough bond so that creepage paths from the conductor to the outside of the module will not occur. The length of the path from the conductor to the outside shall be 0.25 inch, or in accordance with 3.3.4, whichever is greater to assure a sufficient length of bond to prevent breakdown. Provisions shall be made to anchor the wire as it emerges from the encapsulant; or other precautions shall be taken so that subsequent handling does not mechanically stress the bond between the encapsulant and the wire insulation.

3.5.2 Connectors. Connectors shall not be used as high voltage interfaces in Class 1 (1.4.1) equipment unless compliance of such connectors with the requirements of this document is demonstrated by suitable tests called out herein.

3.5.2.1 Venting. The void enclosed between the interface of the mated connector and the other volumes sealed off by cable clamps, etc., shall be vented in accordance with 3.3.12.

3.5.2.2 Insulation. The connector insulation material shall be selected in accordance with 3.4.

3.6 Performance testing. The performance of high voltage parts, components and subsystems shall be substantiated by testing as specified in Section 4 herein.

3.7 Environmental testing. Requirements for type approval (TA) and flight acceptance (FA) tests are stated in 3.7.1 and 3.7.2 respectively.

3.7.1 TA testing. TA testing shall comprise of testing of electronic parts and components (3.7.1.1) and subsystems (3.7.1.2) testing.

3.7.1.1 Electronic parts and components testing. Electronic parts selected for high voltage applications shall be exposed to test conditions sufficiently severe in the critical pressure region to establish margins and to test the design, construction and types of insulation materials used in accordance with 4.3.2. Such parts shall have previously met the requirements of applicable project parts documents. If the parts are encapsulated in the flight subsystem, the parts undergoing part type qualification may be encapsulated in identical material with the approximate thickness and geometrical configuration as the flight model.

3.7.1.2 Subsystem testing. Subsystems, employing high voltages, shall be exposed to operation in the critical pressure region during TA tests, if possible; otherwise a separate test shall be made. The length of time and test conditions shall be as specified in 4.2.2.1.

3.7.2 FA testing. FA testing shall comprise of testing of electronic parts and components (3.7.2.1) and subsystems (3.7.2.2) testing.

3.7.2.1 Electronic parts and components testing. Electronic parts, after meeting the requirements of applicable project parts documents shall undergo FA tests per 4.3.3 for high voltage applications. Flight acceptance test parameters shall be of magnitudes that adequately screen the parts for the intended application without causing degradation or deterioration.

3.7.2.2 Subsystem testing. Subsystems, employing high voltages which are required to operate in a critical pressure region during some portion of the flight mission, shall be operated in the critical pressure region to demonstrate compliance with this document in accordance with 4.2.2.2. Subsystems, employing high voltages which are not required to function in the critical pressure region at any time during the mission and have a record of successful tests per 3.7.1.2, may be specifically waived from this requirement.

3.8 Workmanship. All parts and components intended for high voltage usage shall be manufactured to a high standard of workmanship. Uniformity of shapes, dimensions, and construction shall permit interchangeability of replaceable parts and assemblies. The use of smooth fillets, rounded edges and corners to eliminate points shall be emphasized. There shall be no cracks, breaks, chips, bends, burrs, loose attachments, illegible markings, or other evidence of workmanship defects which could adversely affect the performance of the life of parts and components.

4. QUALITY ASSURANCE PROVISIONS

4.1 General. Inspections and tests as specified herein shall be performed on all subsystems, parts and components used in high voltage applications to substantiate the requirements of Section 3.

4.2 Subsystem testing. Subsystems, employing high voltages, shall be operated in the critical pressure region for both TA and FA tests with instruments of suitable sensitivity to detect any possible corona or arcing occurring in the subsystem (as required by 4.2.2.1, TA; and 4.2.2.2, FA). In addition, suitable corona detection instruments shall be employed during spacecraft system TA and FA tests to monitor for any unexpected breakdowns during such environmental testing.

4.2.1 Test objectives. The principal objective of operating a subsystem employing high voltage in the critical pressure region, as a part of TA testing, shall be to demonstrate the capability of the subsystem to survive operation in this environment. An additional objective shall be to qualify details of design such as:

a. Design concept
b. Adequacy of interconnections
c. Effectiveness of protective devices
d. Effect on other subsystems, and
e. Quality of workmanship.

The objective of operating a subsystem in the critical pressure region for FA tests shall be to verify the quality of workmanship and to detect errors so that intentional or unanticipated exposure of the high voltage electronic equipment to the critical pressure region during flight will not degrade the mission.

4.2.2 Environmental testing. Environmental testing of TA and FA equipment shall include both Classes 1 and 2 equipment.

4.2.2.1 TA testing. The TA tests required in this document are in addition to those test required by the applicable project documents.

4.2.2.1.1 Class 1 equipment. Testing of subsystems, employing Class 1 equipment per 1.4.1 for TA, may be run concurrent with thermal vacuum test if:

a. Corona detection equipment is properly connected into the high voltage equipment and monitored continuously throughout the thermal vacuum test for evidence of corona or arcing breakdown. If the subsystem has inherent corona detection capability which is demonstratable to the satisfaction of JPL, the requirement for external corona detection equipment may be waived.

b. Pressure is held through the 0.1 to 1 torr region for a period of time compatible with the mission profile or 3 days, whichever is longer with the subsystem functioning to specification through all modes of operation. Subsystems, which are not normally exposed to operation in the critical pressure regions (e.g., lunar landers) may be tested by operation at ambient room pressure with the subsystem in the mode most likely to experience breakdown. Then while operating, pump down to 0.1 torr with 30 minutes or less; hold at this pressure for 3 days; then switch through all modes of operation 6 times minimum while monitoring for voltage breakdown. If the number of mode changes is limited so that 6 times is an appreciable fraction of the total allowable, then this number may be revised downward upon specific approval of JPL.

Subsystems, which are required to operate in the critical pressure region at the end of the flight (e.g., Mars Lander) may fulfil the mission profile requirement by being exposed to 10^{-4} torr or higher vacuum for 3 days. Then while functioning in the mode most likely to experience breakdown, the subsystem shall return to 1 torr and shall operate in this region for a minimum of 3 days.

Any indication of corona or arcing on any corona detection network, or from the operation of the subsystem (if the subsystem has inherent corona detection capability) shall be cause for rejection.

4.2.2.1.2 Class 2 equipment. (Refer to 1.4.2.) Tests of subsystems employing Class 2 equipment may be run concurrent with thermal vacuum tests, or a separate test may be performed. Monitoring for voltage breakdown is required by one of the following methods:

a. Suitable corona detection equipment
b. Inherent capability of the subsystems to detect corona, or
c. By visual means.

Prior to turn on, the subsystem shall be exposed to 0.1 to 1.0 torr region for 24 hours. The subsystem shall then be operated in all possible modes while at 0.1 to 1.0 torr region at the high temperature range, where functioning is required in the thermal vacuum test. The length of time of operation in each mode shall be the time at which the approximate temperature equilibrium is established. Upon completion of the tests, the high voltage subsystem shall be disassembled for visual inspection. Degradation of components or damage to the subsystem shall be cause for rejection.

4.2.2.2 FA testing. The FA tests required in this document are in addition to those tests required by applicable project documents.

4.2.2.2.1 Class 1 equipment. Tests of subsystems with Class 1 equipment, which is required to operate in the critical pressure area, may be run concurrently with FA tests, if operation in vacuum is required. If operation in vacuum is not required, then a separate test in a vacuum chamber shall be necessary. Suitable corona detection equipment shall be required to monitor for possible voltage breakdown, unless the functioning subsystem has an inherent capability for corona detection, which has been previously demonstrated. The subsystem shall be exposed to the 0.1 to 1.0 torr region for 6 hours, and then turned on. Operation in each mode shall be of sufficient duration, typically several minutes, to allow a thorough detection opportunity for any corona or arcing which may occur. The presence of corona or arcing shall be cause for rejection.

Subsystems with high voltage equipment, which are normally not required to operate in the critical pressure region, may be exempt from this test if corona-free operation of an identical subsystem was demonstrated during the TA tests of 4.2.2.1, and a special waiver is given by JPL.

4.2.2.2.2 Class 2 equipment. FA testing of subsystems with Class 2 equipment may be waived if adequacy of the protective devices or designs has been demonstrated in the TA tests of 4.2.2.1. Any test required by this section shall be run at 1.0 torr for the minimum time necessary to verify the workmanship and to detect flaws in materials or fabrication. Inspection of the protective devices shall be made after a test. Pitting or burning of the protective devices shall be cause for rejection, unless the defects can be removed by suitable and careful polishing techniques acceptable to JPL prior to flight.

4.3 Electronic parts and components testing. In the following paragraphs, the term "electronic parts" shall be interpreted to include components as defined in 6.1.5.

4.3.1 Test objectives. The main objective of imposing qualification tests on the parts, in addition to those required by applicable parts documents, shall be to determine the suitability of the part for high voltage applications with regards to such factors as:

a. Adequacy of design
b. Quality of workmanship
c. Spacing of leads
d. Stresses caused by high voltage gradients
e. Dielectric materials employed
f. Presence of voids, and
g. Heat dissipation.

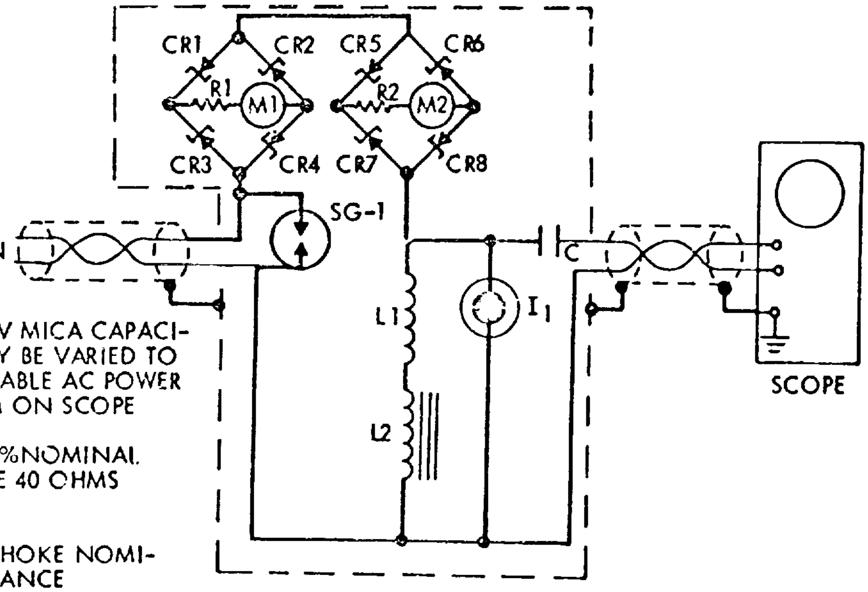
The objectives of performing acceptance tests on high voltage parts, in addition to those previously required by applicable parts documents, shall be to verify workmanship, including detection of errors.

To accomplish these objectives, all electronic parts used in high voltage circuits shall be tested for designated period of time in accordance with the type of test and the test setup specified. These test conditions shall be applicable to all electronic parts except those specially named under appropriate paragraphs of this document. Applicable paragraphs of MIL-STD-202 C, Method 301, which are not in conflict with this document, may be used as a guide for electronic part tests.

4.3.2 General electronic part design qualification. Electronic parts used at high voltages shall be tested for corona or arcing in the critical pressure region to determine the adequacy of construction of the electronic part from the high voltage considerations. Following suitable precaustions to minimize external corona or arcing, the voltages shall be applied while the electronic part is in the critical pressure region. It is expected that applied voltages in design qualification tests will be high enough to cause some failures, in order to establish a margin of confidence. Voltages applied to electronic parts shall be greater than normal operating voltages in order to accelerate failure of marginal or defective components. For convenience in testing, a functional group of electronic parts which form a component of the subsystem may be tested in accordance with this document (rather than for each electronic part separately).

4.3.2.1 Test procedure. Test voltages as given in the respective paragraphs shall be applied to the electronic parts undergoing test in a vacuum chamber at room pressure. Corona detection networks as shown on Figure 7 shall be used in appropriate leads to monitor for corona or arcing. With the voltage continuously applied, the air pressure shall be reduced to the lower limit (see 6.1.3), and this pressure shall be varied between the upper and lower limits several times for the time interval specified in 4.3.2.7. If several voltage tests are to be made on the same electronic part or on several parts in the same chamber, the test voltages may be applied in sequence by switching (provided that the chamber pressure is varied between the limits of 6.1.3 for each test). At the conclusion of the test, the voltage shall be removed, and the electronic parts shall be brought back to ambient room pressure. During the test, any evidence of corona or arcing shall be cause for rejection. Voltage lines and feed-throughs to the component in the test chamber shall be a construction that will preclude the formation of corona.

4.3.2.2 Electronic parts mounting. Electronic parts undergoing test shall be mounted in a similar to that in the subsystem, especially with



C = 300 PF 400 V MICA CAPACITANCE MAY BE VARIED TO OBTAIN USABLE AC POWER WAVEFORM ON SCOPE

L_1 = 2.6 MH ±20% NOMINAL RESISTANCE 40 OHMS AIR CORE

L_2 = 3 H ±20% CHOKE NOMINAL RESISTANCE 225 OHMS

SG-1 SIEMENS PROTECTIVE GAP

I_1 = NE-2 NEON - OPEN CIRCUIT PROTECTION

CR1 - CR8 - 10 V ZENER DIODES

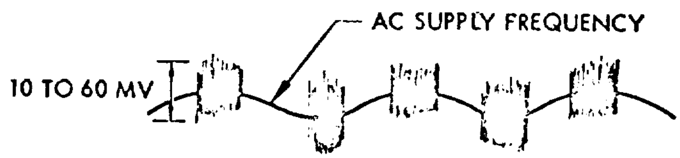
M-1 - 0 - 5 MICROAMMETER (CORONA)

M-2 - 0 - 1 MILLIAMMETER (ARC)

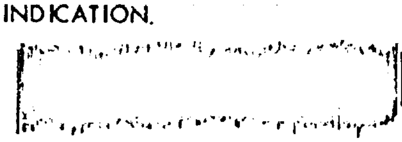
R-1 - MICROAMP CALIBRATION RESISTOR

R-2 - MILLIAMP CALIBRATION RESISTOR

SCOPE- AC CORONA INDICATION



SCOPE- DC CORONA INDICATION.



NOTES:

1. IF ELECTRODE CONFIGURATION IS UNSYMMETRICAL, CORONA BURTS ON ONE POLARITY OF SUPPLY FREQUENCY WAVEFORM MAY BE ABSENT.
2. ABRUPT BREAKS IN SCOPE TRACE OR BURST AMPLITUDES > 0.5 VOLT PEAK-TO-PEAK INDICATE ARCING, RATHER THAN CORONA.
3. SCOPE SENSITIVITY 10 MV/CM.

Figure 7. Corona Detection Network Schematic

regard to adjacent metallic surfaces, terminals, etc. Potting, coating or encapsulation shall be similar to that applied to the electronic part in the complete subsystem.

4.3.2.3 Test voltage amplitude. The test voltage shall be twice the maximum operating voltage. If both ac and dc voltages are applied simultaneously to an electronic part during normal operation, the test voltage shall be an ac sine wave with a peak amplitude equal to twice the sum of the dc and ac operating voltages. If it can be shown that application of the test voltage specified herein will exceed the manufacturer's rating, the test voltages may be reduced to 130 percent of maximum operating voltage upon written approval by JPL (if the objectives of 4.3.1 can still be met).

4.3.2.4 Test voltage frequency. The frequency of the test voltage shall be within ±10 percent of that experienced by the electronic part during normal operation. DC voltages shall not be applied to electronic parts normally operating at ac potentials. Electronics parts, which normally operate on dc voltages, shall be tested by the application of a dc voltage in accordance with 4.3.2.3. Electronic parts which normally operate on ac shall be tested by sine wave voltages of a peak amplitude as specified in 4.3.2.3. If more convenient, a 60 Hz sine wave instead of the normal operating frequency may be used, subject to the restriction that the 60 Hz test frequency shall not be nearer than ±20 percent of the resonant frequency of the part, such a test frequency shall not cause damage to the part, and the normal operating frequency is under 6 kHz. Electronic parts normally operating at frequencies above 6 kHz shall be tested at their nominal operating frequency.

4.3.2.5 Test voltage application. Voltages shall be applied between terminals of the electronic part. If the terminals are insulated from the metallic case or mounting hardware, the test voltage shall also be applied between the terminal and the case or the mounting hardware.

4.3.2.6 Rate of voltage application. The test voltage shall be raised uniformly from nominally zero to the final value at a nominal rate of 500 volts per second, dc or rms, unless otherwise specified.

4.3.2.7 Test duration. The test voltages shall be applied in accordance with applicable paragraphs of this document for the minimum length of time of 1.0 hour in the critical pressure region.

4.3.3 General electronic part acceptance tests. Acceptance tests at sea level conditions of electronic parts for flight subsystems shall be performed on all electronic parts rather than a sampling basis to screen out electronic parts with defective workmanship or concealed damage.

4.3.3.1 Operating test voltage. The voltage applied between the terminals of an electronic part shall be 130 percent of the operating voltage for the test time specified in 4.3.3.5.

4.3.3.2 Insulation test voltages. Transformers with graded insulation shall be exempt from the requirements of this paragraph. In transformers without graded insulation, voltages applied between all the terminals tied together and mounting hardware shall be of sufficient magnitude to stress the dielectric at the narrowest section to 80 percent of the rated dielectric strength of the insulation material for the period of test time specified in 4.3.3.5. Components with no conducting mounts or enclosures shall be buried in metallic shot or have a conducting foil wrapped on the surface of the insulation to serve as the voltage return. Corona detection networks shall be used to monitor possible corona or arcing.

4.3.3.3 Frequency. The frequency of the applied voltage shall be the same as that under normal operating conditions. If this is not practical, then 4.3.2.4 shall apply.

4.3.3.4 Rate of application. The rate of application of test voltages may be instantaneous. The minimum rate shall be as required in 4.3.2.6.

4.3.3.5 Test duration. The minimum time for the full voltage to be applied to the electronic part shall be 5.0 ±1.0 seconds.

4.3.4 Transformer/inductor tests. Qualification tests of transformers and inductors shall be in accordance with 4.3.2. The tests specified in 4.3.4.1

through 4.3.4.5 shall be a requirement for acceptance prior to installation in a subsystem. Part acceptance tests as well as design qualification tests on transformers and inductors shall be performed in the critical pressure region.

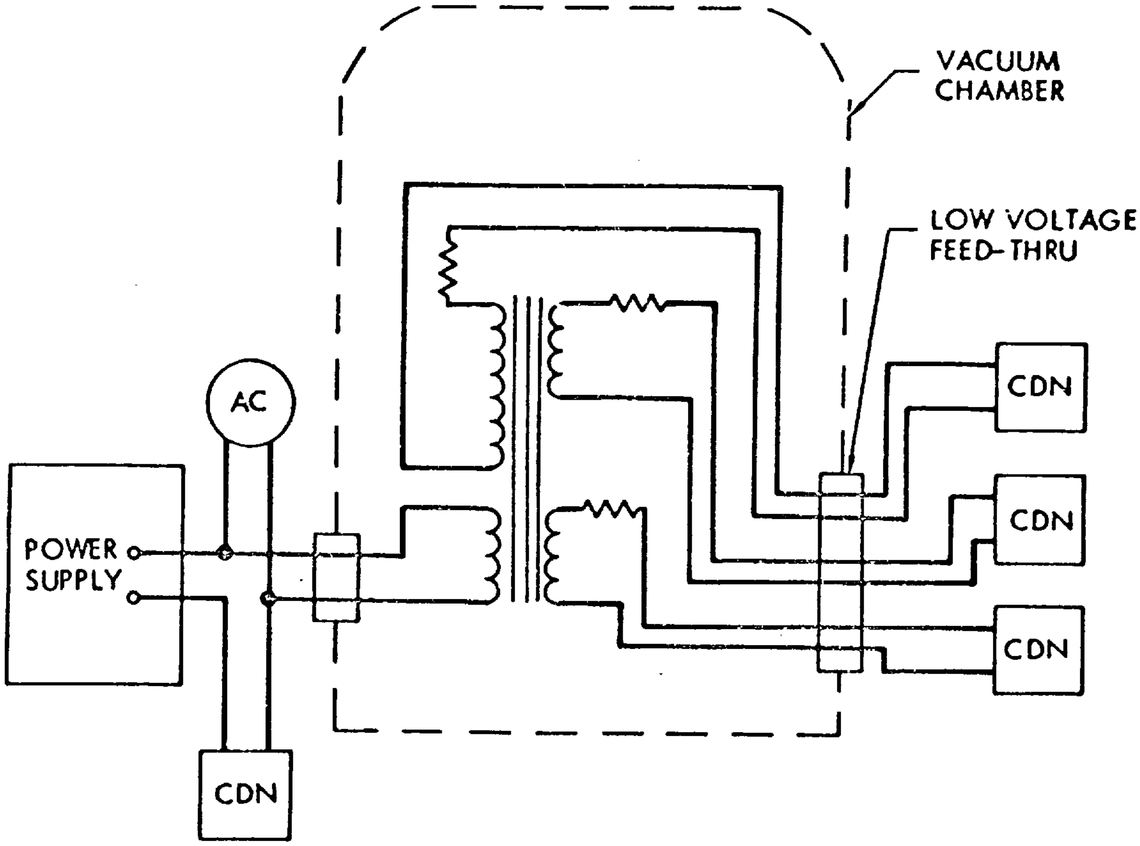
4.3.4.1 Test configuration. The configuration for testing transformers and inductors shall be as shown on Figures 8 and 9. Electrical connectors and wire leads shall be corona proof when the pressure is in the critical pressure region.

4.3.4.2 Interwinding insulation. The insulation integrity between windings, between a winding and the core, and between a winding and the case if one is used, or between windings and mounting inserts, if used, shall be tested by applying a voltage between the various windings, cores, etc., in accordance with Figure 8 and Table I for the length of time specified in 4.3.3.5.

Table I. Interwinding Insulation Test Voltages

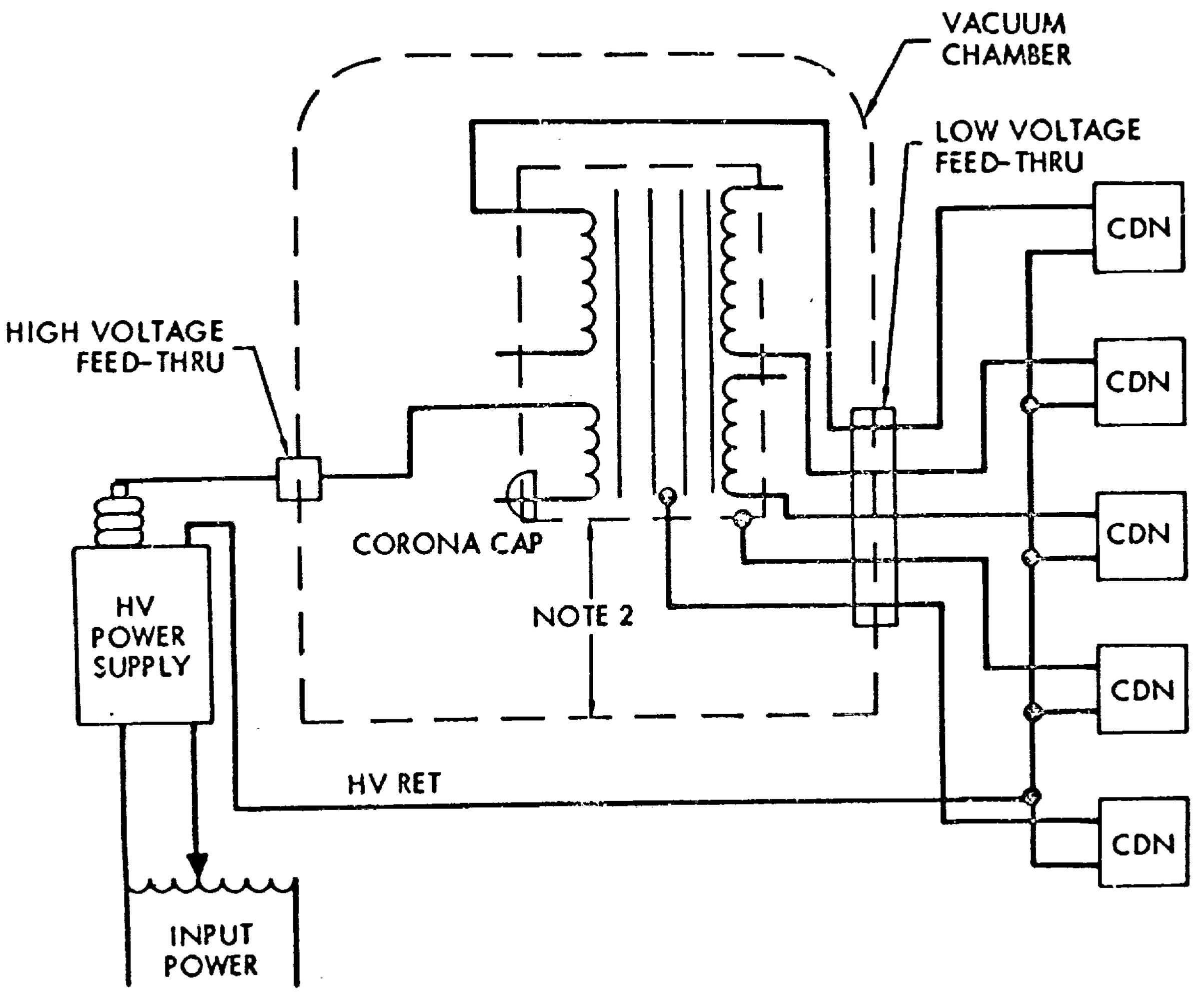
Working Voltage (dc plus peak ac)	Test Voltage (rms)
250 to 700 volts	2.8 x working v.
Above 700 volts	1.4 x working v. plus 1000

4.3.4.3 Intrawinding insulation. Transformers shall be subjected to a voltage sufficient to cause twice the rated voltage to appear across all windings at the critical pressure region. The test voltage may be applied to any winding as shown on Figure 9. Care shall be taken to terminate all transformer terminals so that external corona or arcing is prevented. Mountings and windings shall be grounded as they would be in service. The test frequency shall be far enough from any resonant frequency, so that voltages more than twice rated voltage will not occur in any winding. Twice the rated voltage shall be applied across an inductor winding at approximately twice the normal frequency or in a manner that will not exceed twice rated current.



NOTES:
1. RESISTORS ARE LOADING R'S FOR SECONDARY WINDINGS. (MAY BE LOCATED OUTSIDE OF CHAMBER)
2. NEON INDICATOR I_1 SHALL BE BYPASSED FOR THIS TEST.
3. POWER SUPPLY VOLTAGE SHALL BE TWICE RATED VOLTAGE FOR THE WINDING ENERGIZED WITH THE FREQUENCY RAISED SO THAT AC CURRENT FLOW IS EQUAL TO OR LESS THAN RATED CURRENT.
4. GROUNDING TYPE SELECTOR SWITCH MAY BE USED WITH ONE CORONA DETECTION NETWORK.
5. CDN = CORONA DETECTION NETWORK (SEE FIGURE 2).

Figure 8. Transformer Intrawinding Breakdown Test



NOTES:

1. GROUNDING TYPE SELECTOR SWITCH MAY BE USED WITH ONE CORONA DETECTION NETWORK.
2. TRANSFORMER MUST BE ELECTRICALLY INSULATED (LOW VOLTAGE) FROM VACUUM CHAMBER GROUND.
3. CDN = CORONA DETECTION NETWORK (SEE FIGURE 2).

Figure 9. Transformer Interwinding Breakdown Test

4.3.4.4 Test duration. Test duration requirements shall be as follows:

a. Design qualification: Test duration for component design qualification tests shall be as specified in 4.3.2.7.

b. Component acceptance: Test duration for component acceptance shall be as specified in 4.3.3.5.

4.3.4.5 Examination during and after tests. Components undergoing tests as described in the previous paragraphs shall show no corona or arcing during the test. After the test, components shall be examined for evidence of arcing, flashover, breakdown of insulation, and damage. Visible damage or detection of voltage breakdown or corona by instrumentation shall be cause for rejection.

4.4 Test setup. The test setup shall include the following.

4.4.1 Corona detection network. Detection of corona or arcing shall be by a current or series type of network as shown on Figure 7 inserted in series with the chassis ground return of the high voltage circuit being tested. In cases where the added series impedance in the chassis return is detrimental to the operation of the component or system, the parallel or voltage type described in MIL-T-27C shall be used. Selection of the type detection network used shall be based on the following criteria.

a. The current or series type shown on Figure 7 is composed of low voltage rating elements in the chassis ground or low voltage return side of the circuit, and enables isolation of the of the returns so that the location of the corona may be determined.

b. The high voltage or shunt type specified by MIL-T-27C consists of a high voltage capacitor and inductor in series with the capacitor connected directly to the high voltage terminal and the inductor grounded. The common node provides the input to an oscilloscope. The capacitor shall be corona-free, otherwise, corona occurring in it will be indistinguishable from that occurring in the equipment undergoing tests.

The current or series type of corona detection net work is the only setup that can be used with equipment in which the high voltage connections are located inside the vacuum chamber and are not accessible. An additional advantage of this network shall be that it will be possible to distinguish between corona externally at a component terminal and internally through the case insulation. Corona occurring at a terminal in a vacuum chamber, which is not a defect of the component, will not abort the test by preventing the detection of corona occurring in the component. The parallel type described in MIL-T-27C does not have this capability.

4.4.1.1 Series corona detection network. The current type corona detection network is inserted in series with return or chassis ground lines to monitor the corona or arc current flowing in the circuit. The input to the corona detection network consists of two zener diode rectifier bridges and two inductors, all in series as shown on Figure 7. Meter M1 in the first bridge measures corona currents in the 0 to 5 microampere (μa) range. The second bridge covers the 0 to 1.0 milliampere (ma) range. Currents in excess of 5.0 μa cause a voltage drop of 10 volts across R1; the zener diodes then conduct thus protecting the microammeter from excessive currents. With the microammeter protected, the currents in the 0 to 1.0 ma range due to arcing will be indicated on M2. Arc currents, whether pulses or continuous, in excess of 1.0 ma cause a corresponding 10 volt drop across R2, zener diodes CR-5 to CR-8 conduct, protecting the milliammeter. Inductances L1 and L2 in series provide a significant ac impedance from audio frequencies to nearly 0.5 mHz, the frequency range of corona voltage. The function of the capacitor C is to attenuate the ac supply frequency to a sufficient degree, but to pass the corona burst pulses so that the maximum sensitivity of the oscilloscope may be utilized. The power supply waveform appearing on the oscilloscope serves as a reference for corona bursts, as shown by the waveform sketch on Figure 7. Corona bursts can thus be distinguished from extraneous noise in the circuit. This circuit will operate with either ac or dc corona currents, or combination of both, without switching.

4.4.1.1.1 Network ac operation. The positive and negative sections of the ac current waveform are rectified by alternate branches of the bridge, with the resulting dc passing unidirectionally through the meter circuit. Since the meters cannot distinguish between corona current and any capacitive current, the main reliance for corona indication is the oscilloscope. A typical ac waveform with corona burst is shown on Figure 7.

4.4.1.1.2 Network dc operation. In dc operation, capacitor C1 will attentuate power supply ripple or low frequency noise. The high frequency corona burst may or may not appear on the oscilloscope depending on the geometry, voltage, polarity, and other factors. DC corona indication may also be a burst rather than a continuous smear as shown. In this event, the microammeter will indicate the presence of corona.

4.4.2 Vacuum chamber. The vacuum equipment should have sufficient capacity to pump down to the critical pressure region within 20 minutes with the chamber air and outgassing loads present.

4.4.2.1 Vacuum chamber penetration. Where possible, to eliminate any terminals in a vacuum, all high voltage connections required through the interface may consist of insulated wires embedded in the component and long enough to pass through the vacuum port without splicing. Vacuum sealing can be achieved by "O" ring seals under compression around the wire insulation. A continuous pumping system can tolerate the leakage of these seals, with the moderate vacuum requirements of the critical pressure region. After acceptance, the component leads can be cut to installation length.

4.4.3 Electrical connections. Connections to high voltage, especially ac, terminals of equipment inside the vacuum chamber or splices in high voltage cables should be kept to a minimum. Where such connections are unavoidable, they can be encapsulated in a resilient, easily removable resin using applicable paragraphs of 3.4 as a guide only, because of the temporary nature of the connections. To minimize air bubble formation, the requirements of 3.4.10 should be followed. After polymerization for a high voltage dc connection, a conducting shell of foil shall be wound on the resin and connected to a corona detection network to monitor the connection for corona or arcing. Any voltage breakdown occurring through the encapsulated connection may give a false indication of a voltage breakdown in the component or subsystem. For a dc connection, the insulation integrity shall be monitored by enclosing the encapsulation with a conductive material (e.g., foil) which is connected through the vacuum interface to a corona detection network. An ac connection shall require similar enclosure of the encapsulation with a conductive material, but with the added requirements of 3.3.9. Monitoring of the insulation integrity shall be with the corona detection network which will be more difficult due to the capacitive current possibly masking a low level corona.

4.4.3.1 Switching. Switching of component or subsystem high voltage leads shall be accomplished external to the vacuum system.

4.4.4 Oscilloscope. The frequency response of the vertical amplifiers of the oscilloscope shall be flat from low audio frequencies of 1.0 MHz or higher. Deflection sensitivity of the trace shall be 10 millivolts/cm or higher. The zero trace of the oscilloscope shall be blanked out visually by opaque tape so that the intensity can be turned up sufficiently to see the corona bursts.

4.5 Rejection and resubmittal. High voltage parts and components that fail to meet all the requirements of this document shall be rejected and returned to the contractor. Prior to resubmittal, if applicable, the contractor shall furnish the JPL procurement division representative and the JPL cognizant engineer full particulars in writing regarding the cause of failure and the action taken to correct the deficiencies.

5. PREPARATION FOR DELIVERY

Not applicable.

6. NOTES

6.1 Definitions. Definitions applicable to this document are as follows:

6.1.1 Voltage breakdown. Voltage breakdown as used in this document refers to either arcing or corona.

6.1.1.1 Corona. An incomplete or partial voltage breakdown of the air or gas adjacent to one or both electrodes or conductors, resulting in a current flow of the order of 10^{-7} to 10^{-6} amp rms.

6.1.1.2 Arcing. A complete voltage breakdown of dielectric between two conductors, with currents of the order of milliamperes or higher, limited only by power supply impedance.

6.1.2 Damage. Damage within the requirements of this document is hereby defined as any degradation, deterioration, or gross change in a circuit component or subsystem that would significantly shorten its operating life or cause permanent out-of-tolerance change in performance.

6.1.3 Critical pressure region. The range of pressure through which the dielectric strength of the air reduces to 20 percent or less of the dielectric strength of 20°C and sea level pressure, shall be the critical pressure region for the purpose of this document. Nominal limits of the critical pressure region in air are 50 torr (60,000 feet altitude) to 5×10^{-4} torr (310,000 feet altitude).

6.1.4 Electronic parts. In this document electronic parts refer to common items such as resistors, capacitors, transistors, and diodes.

6.1.5 Components. A component consists of several electronic parts assembled, interconnected, to perform a function not possible with single part: e.g., diode bridge, filter network, regulator and cable harness.

6.1.6 Equipment. Equipment refers to a collection of components and parts to perform a function such as power supply and modulator.

6.1.7 TA. Designates Type Approval or qualification tests.

6.1.8 FA. Designates Flight Acceptance level of tests for flight parts, components, or equipment.

APPENDIX 2

HELIOS—A AND —B
EXPERIMENT 7 POWER SUPPLIES

May 14, 1971

GSFC Specification 31187B

Helios A & B Missions

Detector Bias Supplies and Low Voltage

Power Supplies for Experiment 7

1.0 INTRODUCTION

This specification describes power supplies which will be utilized in a cosmic radiation experiment for the Helios A & B missions, a German-U.S. cooperative project. These supplies provide the biases required for the solid state detectors and the x-ray proportional counters; the voltage required for the PHA and coincidence system described in Specification 31187A; and other voltages as described in Sec. 3.1.3.1. Mission lifetime is at least two years. Reliability and quality assurance of these systems is of the utmost importance, and considerable effort in these areas will be required. In addition, weight and power requirements are extremely stringent and must be rigidly adhered to in the conception and design of these systems.

2.0 APPLICABLE DOCUMENTS

The documents listed below form a part of this specification to the extent specified herein. In the event of conflict between this specification and those of any of the following documents, the requirements of this specification shall prevail.

S-702-P-1A, Specification for Reliability and Quality Assurance Provisions for Helios Project Instruments, Goddard Space Flight Center, August 7, 1970.

3.0 ELECTRICAL CHARACTERISTICS

3.1 General

The power converter is supplied 28 volts ± 2% at its input terminals from a solar-cell/chemical-battery power system. The low voltage outputs power both low-level analog circuitry and fast digital circuitry. Thus, isolation of these two classes of output from each other as well as from the detector biases is required in order to keep ground looping and system noise to a minimum.

3.1.1 Converter Input Characteristics

3.1.1.1 Voltage - The regulated output voltage from the main spacecraft inverter is 28.0 volts. Connector, relay and wire resistances are in series with the 28 volts. You are to assume that the regulation is ± 2% at the converter input. The experiment power bus is energized through a spacecraft relay by command.

3.1.1.2 Ripple and Noise Tolerance - Except for transient excursions described in 3.1.1.3 below, the power supply shall be capable of operating within specifications when the input power includes electrical noise of 1.5 volts peak to peak in the frequency range 4 Hz to 5MHz.

3.1.1.3 Transient Voltage Excursions - Temporary loss of power may occur at any time as the S/C power distribution system automatically dumps loads to protect itself from an overloaded condition. Experiments would then be turned on one at a time by command. Additionally, transients can occur when the spacecraft switches between redundant regulators, etc. Thus, the S/C has imposed the following survival tests for spikes on the power lines. In the frequency range 2 Hz to 20 KHz, the amplitude of the spikes (pos. and neg.) is to be 7 volts. For a single pulse, the amplitude shall be 28 volts, positive and negative. All pulses are referenced to 28 volts dc and the pulses will rise to peak values in 1 microsecond and decay to zero in approximately 10 microseconds. Additionally, the power supply shall be designed to survive application of 35 volts dc indefinitely and 56 volts dc for at least 100 milliseconds.

3.1.1.4 Source Impedance - The model of the spacecraft power output is a voltage source of 0.1 ohms inherent resistance shunted by 500 μF. To this must be serially added the 0.3 ohms of the harness, connectors, etc.

3.1.1.5 Power Switching - The spacecraft delivers a power synch signal for synchronization of the experiment power converters. It is specified as follows:

a. frequency: 39,947 KHz

b. frequency accuracy: 10^{-4}

c. duty cycle: 1:2

d. Accuracy of duty cycle: $\pm$ 10%

e. Rise/Fall time: $\leq 1\ \mu sec$

f. Input "0": 0 to 0.7 volts

g. Input "1": + 2.0 to + 5.5 volts

h. Reference: + 28 volt return line

i. Source Resistance: $1\ K\Omega < R_S < 1.2\ K\Omega$

It is intended that the power converter divide the incoming synch frequency by 2 and thus that the converter operate at 19,973 Hz. All primary side circuitry must operate from + 28 volts to the + 28 volt return line.

3.1.1.6 Input Grounding - Note that the mechanical chassis of this power supply will be attached directly to S/C chassis ground. The input voltage and input return are delivered on a twisted pair, and the maximum capacitance allowed from either line to chassis ground is 1000 pf.

3.1.1.7 Turn-on Current Limitation - The turn-on current in excess of the nominal current must average to less than or equal to 0.5 milliampere-seconds during the 1 millisecond period following turn-on.

3.1.1.8 Reflected Ripple - When operating from the power source described in Sec. 3.1.1.4 and fully loaded, the converter shall not feed back on the S/C power bus electrical current noise in excess of that shown in Fig. 3.11 and 3.12. The limits for radiated emission are given in Figs. 3.13 and 3.14.

3.1.2 Operating Characteristics

3.1.2.1 Frequency - The converter may operate at 19,973 Hz as described in Sec. 3.1.1.5 or at any frequency in excess of 200 KHz, or separate sections may operate at different frequencies (e.g. the low voltage at 19,973 KHz and the high voltage at 350 KHz, for instance). The choice of operating frequency should be made on the basis of converter efficiency, weight and RFI considerations.

3.1.2.2 Starting Time - The low voltages shall be within limits at full load within 20 seconds after being off at least two hours at any operating temperature. The detector bias outputs shall exhibit a delayed turn-on/off characteristic described later in this specification.

3.1.2.3 Efficiency - The available power for this mission is seriously limited, thus as high an efficiency as possible is required. Design goal shall be 80%. Converter designs which provide less than 75% efficiency at any temperature or input voltage within the nominal requirements of this specification, when the outputs are nominally loaded as listed below, are not acceptable.

3.1.3 Low Voltage Output Characteristics

3.1.3.1 Low Voltage Outputs - The low voltage outputs required, and the nominal load on each are as follows:

Voltage or System	Current	Power
+ 12 volts	8 ma	96 mw
+ 7.5 volts	128 ma	997 mw
+ 4.7 volts	60 ma	282 mw
- 2.0 volts	80 ma	160 mw
- 10 volts	1 ma	10 mw
PHA & Coin System, Spec 31187A		930 mw
Detector Bias Supplies		150 mw
	Secondary total	2.625 watts

In computing the above total we have assumed that the PHA and coincidence system described in Specification 31187A required 930 mw. This estimate is extrapolated from our past experience. Note that the - 10 volt bias may be any stable voltage from - 10 to - 15 volts. For this calculation we have assumed that the bias supplies require 150 mw, operating from regulated secondary voltages. However they may operate from the primary 28 volt source if the proposer wishes.

At 80% efficiency with a 28.0 volts bus at 23°C, this load of 2.625 watts will draw 3.28 watts from the bus, and at 75% efficiency will draw 3.50 watts.

3.1.3.2 Regulation - The + 4.6, and - 2.0 outputs are used for digital applications. They shall be constant within ± 4% for all temperatures and input conditions specified, and for all load conditions from 0.7X to 1.3X nominal as listed above.

All remaining low voltage outputs shall be constant within $\pm$ 1.5% for all temperature and input conditions specified, and for all load conditions from 0.7X to 1.3X nominal as listed above.

3.1.3.1 Ripple Content - The maximum ripple and noise content on any low voltage output under any combination of environmental, input, and output loading conditions specified, shall not exceed 10 mV, peak to peak. Ripple shall be measured at the output terminals with the converter fully loaded and with an oscilloscope of DC to 50 MHz bandwidth.

3.1.1.4 Grounding - Output circuit common for the digital outputs shall be separate from the output common for all remaining output voltages, and of course both shall be isolated from input common as specified above. The common for the detector biases shall be separate from both the digital and analog voltages. Note that the experiment will tie the secondary grounds together.

3.1.3.5 Short Circuit Protection - The converter must be designed so that a short circuit condition on one or more outputs will not cause permanent damage. This includes short circuit or any of the detector bias outputs as well.

3.1.4 Detector Bias Output Characteristics

3.1.4.1 Solid State Detector Biases - The converter shall supply bias voltages for use on the solid state detectors as listed below. The maximum load shown occurs only at the high temperature extreme, while the minimum load occurs at the low temperature extreme. The nominal load should be used for purposes of satisfying Sec. 3.1.3.1.

Voltage	Current		
	Minimum	Nominal	Maximum
500 V	1 μa	30 μa	150 μa
55 V	0.1 μa	1 μa	10 μa
25 V	0.1 μa	1 μa	8 μa

3.1.4.2 Regulation - The solid state detector bias outputs shall be within ± 3% of nominal for all conditions of temperature, input voltage and output load from zero to maximum current as shown in 3.1.4.1.

3.1.4.3 Ripple and Noise Content - The bias supply outputs must contain an absolute minimum of ripple and noise. Under no conditions shall the solid state detector biases contain more than 10 mv peak to peak in any frequency region. Ripple and noise shall be measured at the converter output terminals with an oscilloscope of DC to 50 MHz bandwidth. The measurement shall be made for minimum, nominal and maximum load. Input and output commons must be isolated.

3.1.5.5 Proportional Counter Bias - The proportional counter requires a nominal bias of 1600 volts. The design of the supply should allow for adjustment in this output bias in approximate 25 volt steps to ± 100 volts of the 1600 volts. The load current is usually near zero, but design for a 0.5 μa nominal load and a 2 μa maximum load. The selected proportional counter bias shall be within 0.2% of nominal for all conditions of temperature, input voltage and output load from zero to maximum current. The noise and ripple specification 3.1.4.3 applies.

3.1.4.5 Grounding - Bias output common shall be isolated from the digital and analog supply commons. The experiment will make the connections between commons in the final wireup. Bias common will always be isolated from the + 28 volt return as previously specified.

3.1.4.6 Turn-on Characteristics - Any transients on the bias outputs are coupled to the input of the low-level charge-sensitive preamplifiers. The turn-on and turn-off characteristics of the bias outputs shall be slow to avoid damage to the preamps. This requirement includes a slow decay or rise due to input voltage drop-out. Specifically, the turn-on/off characteristic shall be similar to a ramp or exponential shape, with at least 3 seconds between the 10 and 90% points, and preferably 5 to 10 seconds.

3.1.4.7 Special Considerations - The high voltage outputs shall be such that with no power applied to the input, 25 volts may be applied to the 25 and 55 volt outputs. The DC impedance of the un-powered outputs shall be such that not more than 20 nA will flow into the converter outputs from the external source. 100 volts may be applied to the 500 volt output with a converter design such that less than 50 nA will flow into the converter outputs from the external source.

3.1.5 Alternate Load Specification

For those proposers who wish to bid on the power/bias supplies exclusive of the PHA and coincidence system per Specification 31187A, we have assembled a voltage/current specification for bidding purposes. The exact voltages other than those explicitly given in Sec. 3.1.3.1 will not be known until the PHA and Coincidence system contractor is selected. At that time, negotiations will proceed with those proposers who are in the competitive range.

Voltage	Current	Power
+ 12	8 ma	96 mw
+ 7.75	128 ma	997 mw
+ 6.0	60^{+}ma	361 mw
+ 4.7	60 ma	282 mw
+ 3.0	69 ma	207 mw

Voltage	Current	Power
- 2.0	80 ma	160 mw
- 6.0	60^{+}ma	361 mw
- 12.0	1 ma	12 mw
Detector biases		150 mw
	Secondary Total	2.626 watts

All other specifications apply exactly.

4.0 MECHANICAL CHARACTERISTICS

4.1 Packaging

Outline drawings of the low voltage converter and the detector bias supplies are shown in NASA/GSFC drawings GD-1324980 and GC-1324981 respectively. The locations of the mounting holes are called out, but a proposer can propose alternate locations on the same faces. Similarly, the location areas for the interconnection terminals are specified. Since weight and efficiency are of primary concern, all dimensions should be taken as maxima.

The detector bias supplies may be broken into two assemblies if desired, one for the solid state detector biases and one for the proportional counter supply (1600 volts). In this case, the solid state detectors bias supply should package well within the specifications of drawing GC-1324981. It is our thought in writing this paragraph that it may be to our advantage to mount the proportional counter power supply directly to the top flat surface of the proportional counter itself, thus minimizing the cable runs, interconnection problems, etc. There is a wide range of acceptable packaging arrangements for the proportional counter power supply, but the precise details will have to be worked out after the precise mechanical details of the proportional counter are firm.

4.2 Weight

The complete converters with digital, analog and detector bias outputs are assigned 390 grams or 0.86 pounds. This weight includes the weight of all shielding necessary to meet the rfi requirements.

4.3 Heat Sink

The large flat mounting surface of the low voltage power supply will be in direct contact with the experiment baseplate which is a good thermal sink and which will never exceed + 30° C in flight. Note that the chases of these power supplies will be attached directly to S/C chassis ground, and that galvanic isolation between chassis ground and the + 28 volt return line and the power supply grounds (experiment signal ground) must be maintained. The maximum capacitance allowed between (1) the 28 volt power line and chassis ground and (2) the power supply grounds (summed) and chassis ground is 1000 pf for each of the two cases.

4.4 Thermal Range

The qualification limits for this experiment are - 40°C and + 40°C. All electrical performance specifications hold over this range, and the contractor must test the system over this range, document the tests to verify the performance and furnish such documentation with each delivered unit.

4.5 Vibration Tests

The launch vehicle presently assigned to these missions is a Titan-Centaur. The following tables summarize the qualification levels for vibration and shock.

4.5.1 Sinusoidal Vibration Test Schedule

Axis	Frequency Range	Acceleration
	Hz	g's (0-peak)
Thrust	5-10	0.45 inches(d.a.)
	10-50	15
	50-150	23
	150-200	10
	200-2000	4
Lateral	4-9	0.45 inches(d.a.)
	9-30	12
	30-100	25
	100-200	10
	200-2000	4

The rate of change of frequency shall be 2 octaves per minute.

4.5.2 Random Motion Vibration Test Schedule

Axis	Test Duration (min)	Freq. Range (Hz)	PSD (g^2/Hz)
All three axes	4.0 per axis	20-200	6 db/octave to 0.1125 g^2/Hz at 200 Hz
		200-2000	0.1125 g^2/Hz

Overall level 14.4 g rms duration 4 minutes each axis.

4.5.3 Acoustic Vibration

Each instrument will be tested for susceptibility to acoustic shock by subjecting it to programmed noise per method 515, MIL-S-810 to the following levels for a total duration of 2.0 minutes.

Octave Band Center Frequency	Sound Pressure Level Ref: 0.0002 microbar
16 Hz	123 db
31.5	128
63	135
125	141
250	144
500	142
1000	137
2000	133
4000	132
8000	132
Overall	148

4.6 Interconnection

For reliability and weight considerations, all input and output connections will be by solder terminals except for the low voltage power supply (ref. drawing GD-1324980). If connectors can be included within the weight constraints, only Cannon Royal D, single density connectors will be considered. All connectors will be furnished in a non-magnetic version by NASA/GSFC. In the case of solder terminals, use of a pigtail cable with connector is encouraged to facilitate connections for testing and, if used, should remain attached when delivered. The pigtail would be used for all testing and integration at GSFC up to final assembly. This would eliminate unnecessary soldering and un-soldering of wires on the terminations.

Wherever practicable, connections between these terminals and internal printed circuits shall be accomplished by means of insulated wire at least one-half inch long. This is to prevent overheating pads or crystallizing solder when connections are made to the terminals.

4.7 Construction and Materials

Circuitry may be designed using printed circuits, integrated circuits, thick film, thin film, welded-wire modules, point-to-point wiring, soldering or any combination thereof. The converters shall be conformally coated. Polyurethane coatings are preferred and should be selected with the concurrance of NASA/GSFC to ensure compatibility with the silicon nuclear particle detectors within the experiment.

Particular care shall be taken in surface preparation to insure complete adhesion of potting material to all components and surfaces.

Construction and assembly techniques shall be such that reliable repairs are possible should any part fail.

Non-magnetic materials shall be used wherever possible. Nickel wire is not acceptable in the welded construction. Magnetic shielding material may not be used without the concurrence of the technical representative. See Sec. 6.0.

5.0 PARTS SELECTION

Parts shall be selected on the basis of proven qualification in a space flight application. All parts on the current NASA/GSFC Preferred Parts List are candidates. An additional list of parts is included within this specification (Sec. 5.1).

All parts should be purchased to the appropriate MIL specification as listed in the parts lists. All semiconductors should have a precap visual inspection to MIL-STD-883, Method 2010.1, Condition A or to the manufacturer's standard in-house viaual inspection which is comparable to the MIL-STD-883 test method and conditions indicated above (NASA/GSFC approval is required for this latter step). All parts should be screened as outlined in the GSFC Preferred Parts List, Appendix C, Screening of Electronic Parts for Flight Equipment. This Appendix is attached to this specification. Parts should be serialized, with the exception of carbon resistors and ceramic capacitors, prior to electrical screening.

All parts must receive formal, written approval by NASA/GSFC before a contractor can finally commit his design to them. A complete list of all parts and their purchase specifications must be furnished to NASA/GSFC. Approval or disapproval of parts from the current NASA/GSFC Preferred Parts List will occur within 5 working days of GSFC receipt of the list. Approval or disapproval of parts not on the current NASA/GSFC Preferred Parts List will occur within 15 working days of GSFC receipt of the list.

Component packages other than standard can be considered--e.g., a transistor normally supplied in a metal TO-5 package can be specified in a ceramic flat package which is hermetic and of low magnetic signature; however, the part will be subject to approval/disapproval as a part not on the GSFC Preferred Parts List. Any part carrying a special or house number designation shall be described by means of the procurement specification including electrical parameters before the part can be considered for approval/disapproval.

5.1 Additional Acceptible Parts

Type	Manufacturer, Code
Capacitor, low TC	Vitramon VY10, VY15
Resistor, variable	Bourns, 3082 Cermet
Zener Diodes	Fairchild, FCT 1121-1125
Tunnel Diode	Gen. Electric, STD-860
Hot Carrier Diode	Hewlett Packard, HP2800
Op. Amp.	National, NH0001F/883
Const. Current Diodes	Motorola, 1N5291-1N5297
Transistor	Solitron, 2N3751

The above parts have been listed by the manufacturer's common designation. However, they should be procured to the highest existing MIL specification available at the time of procurement; viaual inspection to the conditions of MIL-STD-883 should be specified for semiconductors; and they should undergo the screening called out in Appendix C of the GSFC Preferred Parts List.

6.0 MAGNETIC REQUIREMENTS

The Helios spacecraft is a magnetically clean spacecraft. The design of the systems specified here must meet the following specifications. The maximum tolerable field in the three orthogonal directions should each be less than that listed as maximum for the radial field measurements.

Test Condition	Maximum Radial Field at 18 Inches
1. Post 30 gauss deperm	1.0 gamma
2. Post 15 gauss exposure	16 gamma
3. DC Stray field	0.1 gamma
4. Perm field after power ON/OFF	1.0 gamma

7.0 QUALITY ASSURANCE AND RELIABILITY

High reliability of the system shall be assured by choice of good design, inspection and testing. The supplier shall maintain an effective and timely reliability and quality assurance program which satisfies at a minimum the requirements of GSFC Specification S-702-P-1A, "Reliability and Quality Assurance Provisions for Helios Project Instruments. Monitoring of the supplier's inspection system will be accomplished through the combined efforts of NASA/GSFC personnel and the designated government inspection agency. The authority and responsibilities of the government inspection acency will be defined subsequent to contract award by GSFC through a letter of delegation to the inspection agency.

Inspection standards shall be established at the part, component, module or board, and systems levels to detect fabrication errors, contamination, poor workmanship, etc. Inspection shall be on a 100% basis.

7.1 In-Process Inspection

The physical in-process inspection of the equipment produced for flight use only shall be performed in a sequence specified by a production flow chart to be submitted. All inspections shall be documented or approval indicated by QC stamps on the assembly print or QA traveller on each module and made available to NASA upon request.

7.2 Receiving Inspection

100 per cent of electrical and electronic parts for the flight units shall be inspected for visual damage prior to assembly. Particular emphasis shall be placed on those characteristics for which deficiencies may not be detected during subsequent inspections and tests.

7.3 Changes

The contractor shall notify GSFC of any proposed changes in design, fabrication method, inspection procedure, or process previously approved by GSFC, including changes which may affect the quality of the end-item, and obtain written approval of the change from the GSFC Technical Representative.

7.4 Parts Records

During fabrication and test of all units, installation of all serialized parts (with the exception of carbon resistors and ceramic low voltage capacitors) and contractor serialized modules will be recorded on assembly prints and test records to scrupulously maintain traceability of piece parts within each system. All GFE parts will be screened and serialized before shipment to the contractor for assembly. Contractor manufactured electronic parts, such as thick film wafers, will be serialized by the contractor.

7.5 Parts Control

All electronic parts and materials to be used in this system shall be controlled and segregated to avoid intermixing of Helios parts with those of any other program. Helios parts and materials shall be stored in a restricted area or locker clearly identified and which may be secured against unauthorized entry. They shall be subjected to a minimum amount of handling, and if necessary, handling shall be done by a limited number of authorized personnel.

7.6 Age Control and Life Limited Products

Parts and materials which degrade with age or use shall be marked to indicate when useful life was initiated, and the time or cycle of expiration at which useful life will be expended.

7.7 Identification Requirements

At the time of manufacture of each module, the installation of a serialized part shall be recorded by serial number on an assembly print designating the serial number of the wafer, module or assembly. Each part, component, module or assembly destined for a Helios flight unit shall be uniquely identified and suitably marked.

8.0 OPERATIONAL TESTING AND DOCUMENTATION

8.1 Operational Testing

Operational testing of each power supply system shall include at least the following throughout the range of temperature - $40^{o}C$ to + $40^{o}C$:

1. Measurement of each output voltage when all outputs are simultaneously loaded at 0.7X, 1X, and 1.3X nominal at both high and low input limit (i.e. 28 V $\pm$ 0.5 V).
2. Photographs of ripple waveform and content under the conditions specified above and with input ripple and noise added per 3.1.1.2 and 3.1.1.3. This need be done at room ambient only. Output waveforms shall be observed during temperature tests, and deviations from the photographed pattern noted in the test record. Peak to peak value of ripple and spiking shall always be recorded in the test log.
3. Input current under each of the conditions specified in (1) above.

4. Calculation of efficiency under each of the conditions specified above.
5. Frequency(ies) of operation as a function of load and temperature.
6. Verification of proper starting and proper interface characteristics with the 28 V input source.

Performance parameters as listed above shall be recorded in a system log book or other suitable form, and will be delivered with each system.

Final temperature testing prior to shipment is subject to witness by the NASA technical representative, or his designee.

Environmental qualification testing will be conducted by GSFC to the levels indicated in this specification.

8.2 Module Testing

Module operational testing data, if any, taken on completed flight modules shall be recorded on data sheets or in a log for each module. Each data sheet or page shall contain the module type, part number and serial number. In addition, the data sheets shall contain part numbers and serial numbers of all transistors and/or diodes utilized in each module or alternately reference an assembly print where this information may be found. Individual and/or spare modules shipped to GSFC shall be accompanied by a copy of the respective operational test data sheets and/or assembly prints with part serialization included.

8.3 System Testing Documentation

A chronological log record shall be completed for each flight system which shall include the following information:

a. System name

b. Serial number

c. Serialized components list which contains all modules installed in the system by matrix module positions, type number and serial number. This is to provide ultimate traceability of each part into a system through a serialized module.

d. Module Operations Test Data Sheets as applicable.

e. Test and Inspection Summary which includes a description of all failures or unusual performance, operating and physical discrepancies observed and all repairs or adjustments made.

f. Certification of compliance with the requirements of the specification.

A copy of this log record shall accompany each flight system assembly shipped to NASA/GSFC.

8.4 Acceptance Testing for Delivery

The flight systems will be officially accepted by GSFC only after a full exercise of each system over the range of electrical and thermal requirements of this specification at the cóntractor's facilities and following vibration and shock tests at GSFC. GSFC is responsible for carrying out the vibration and shock testing within seven working days of actual delivery. Final testing at the contractor's facilities is subject to witness by technical representative or his designee.

8.5 Documentation

In addition to the orderly compilation of test data required by this specification, the contractor shall provide a complete set of circuit schematics; a parts list identifying manufacturer and type for all parts; a circuit performance description; and full assembly print for all modules and mother boards, showing PC interconnect patterns and location of parts referenced to schematic designations; and a complete set of mechanical drawings.

8.6 Marking

Each module, circuit board and package shall be unambiguously marked. Individual modules must be individually marked in a consistent manner to be determined by the contractor, so that no two modules can be confused.

8.7 Data Package

The data package which is referred to in the statement of work is made up of the documents required by Sec. 8.1, 8.2, 8.3 and 8.5.

8.8 Monthly Reports

The contractor shall submit a brief letter-type report covering the activities, progress and problems of a given month. The report shall be submitted by the 10th of the following month. The first monthly report will include an informative milestones schedule and subsequent reports will assess progress relative to this original schedule.

9.0 DISPOSITION OF NON-CONFORMING PARTS AND ASSEMBLIES

During the electrical screening process, rejection of more than 10% of a parts lot is cause for a telephone report to the technical representative within one working day. Subsequent to screening, when any part is rejected for any reason, or fails or malfunctions at any time, the technical representative shall be notified within 24 hours by telephone. The part or parts shall be removed carefully, and segregated from / conforming items and held for GSFC review. In general, all items will be returned to GSFC for failure analysis.

All instrument malfunctions which occur after initial assembly shall be reported to the technical representative by telephone, within 24 hours. Systems exhibiting minor deviations in performance from specifications may be submitted for acceptance upon concurrence of the technical representative.

10.0 EXCEPTIONS TO REQUIREMENTS OF THESE SPECIFICATIONS

If a proposing contractor takes exception or proposes an alternate to any specification or requirement stated within these specifications, he must describe the exception and his reasoning in detail in his proposal. Specifically, if minor relaxation of of certain specifications would significantly increase efficiency or decrease weight, or improve schedule considerations, such items should be discussed in the technical proposal.

11.0 SCHEDULE

Ultimately it is anticipated that four units will be procured as a result of this specification. Three units will be the subject of the original contract with the fourth unit to be an option to be exercised by NASA/GSFC by August 1, 1972.

	Delivery to GSFC
Unit #1	24 weeks after award
Unit #2	35 weeks after award
Unit #3	46 weeks after award
Unit #4	November 1, 1972

The limits for radiated emission are given in Figs. 3.13 and 3.14.

List of Figures, etc.

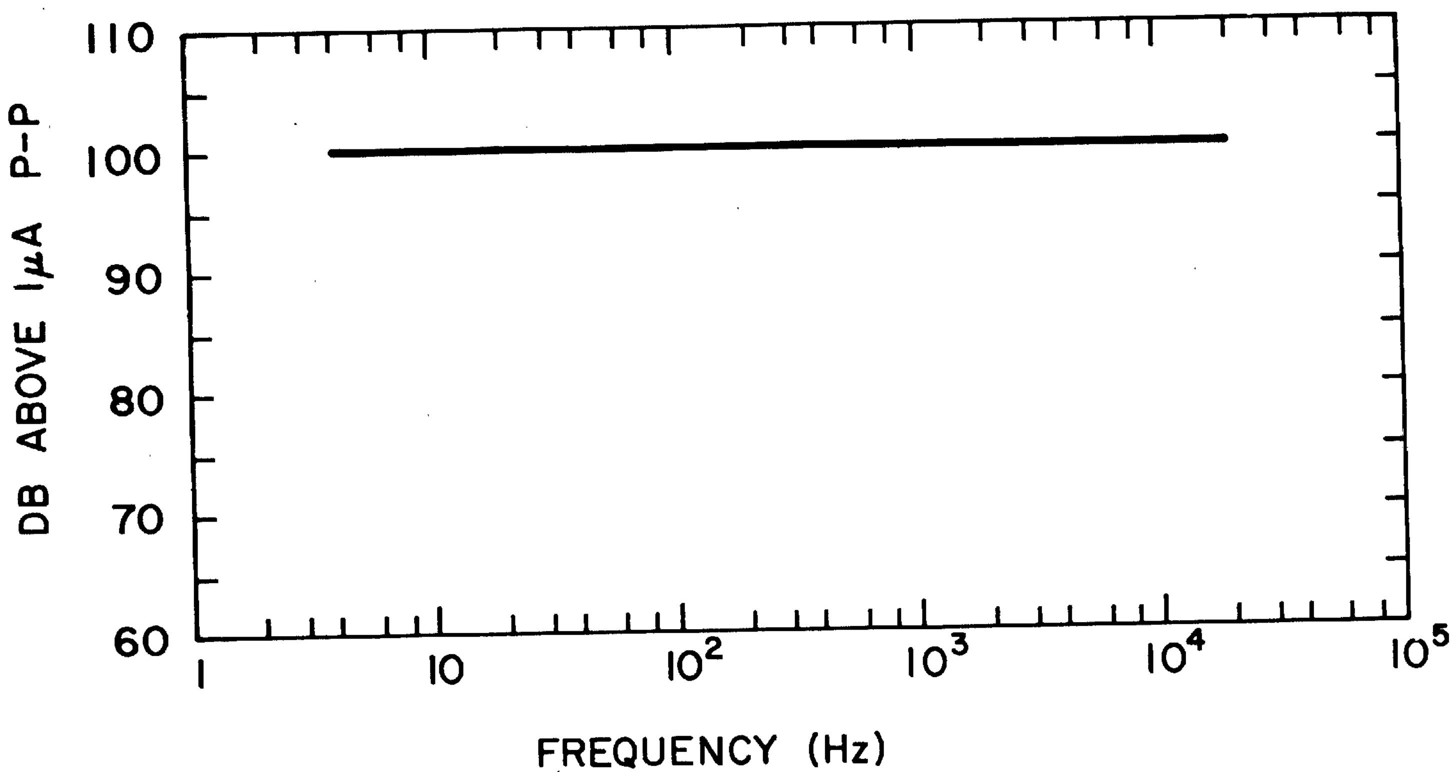


Fig. 3.11

LIMITS FOR CONDUCTED EMISSION, 4Hz-100KHz

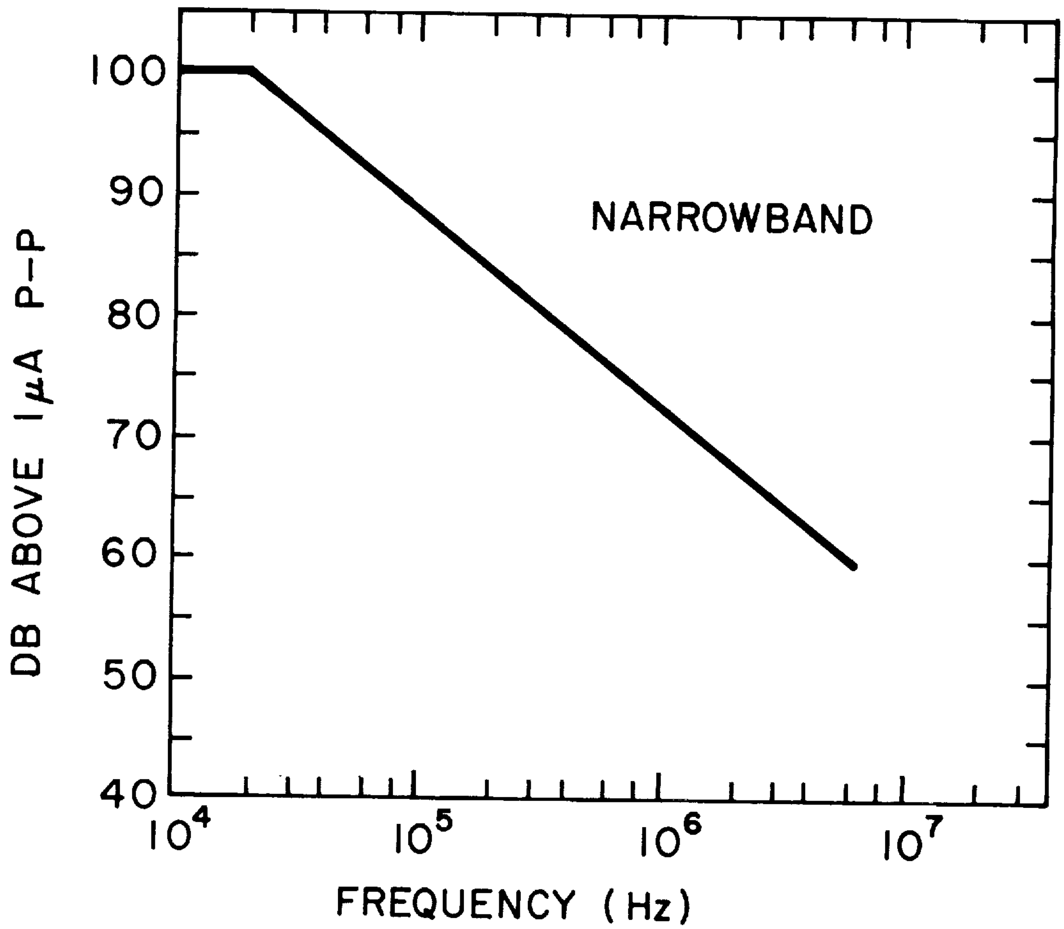


Fig. 3.12
LIMITS FOR CONDUCTED EMISSION,
100 KHz-6 MHz

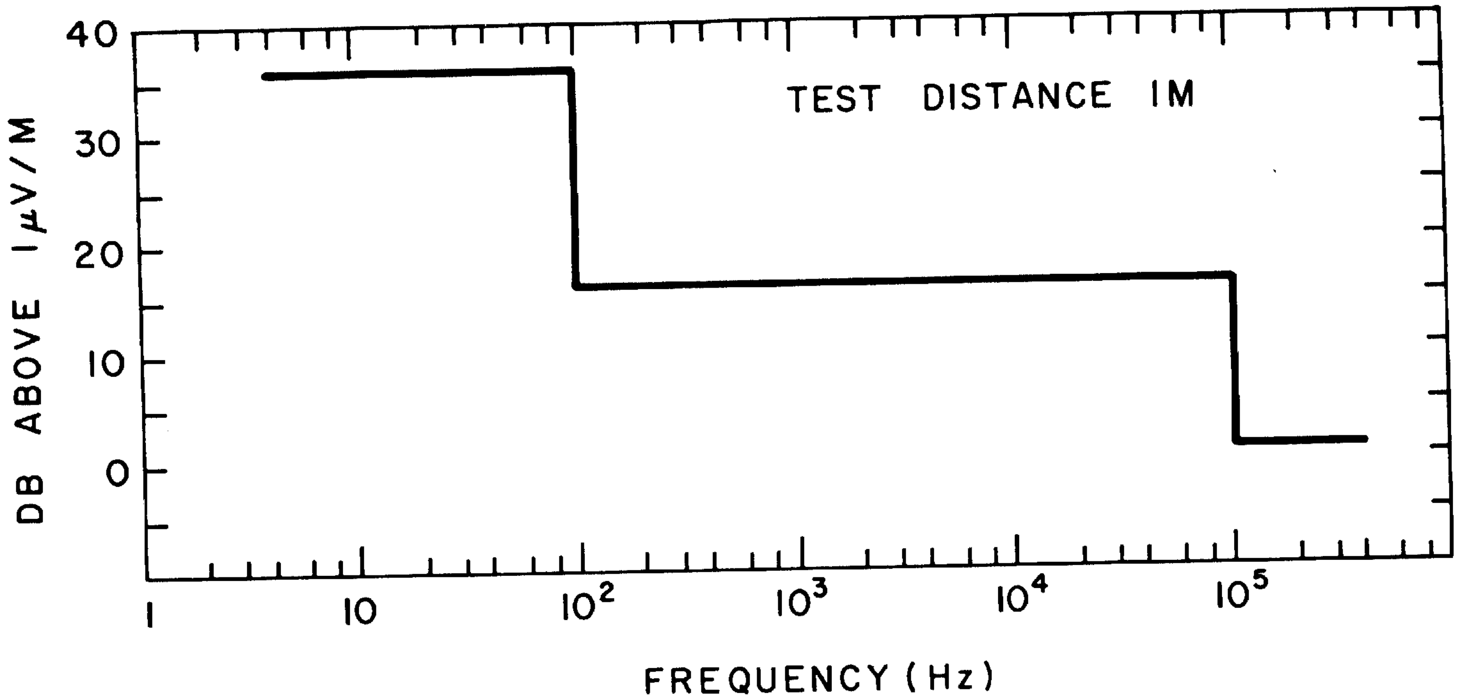


Fig 3.13

LIMITS FOR RADIATED EMISSION
ELECTRIC FIELD

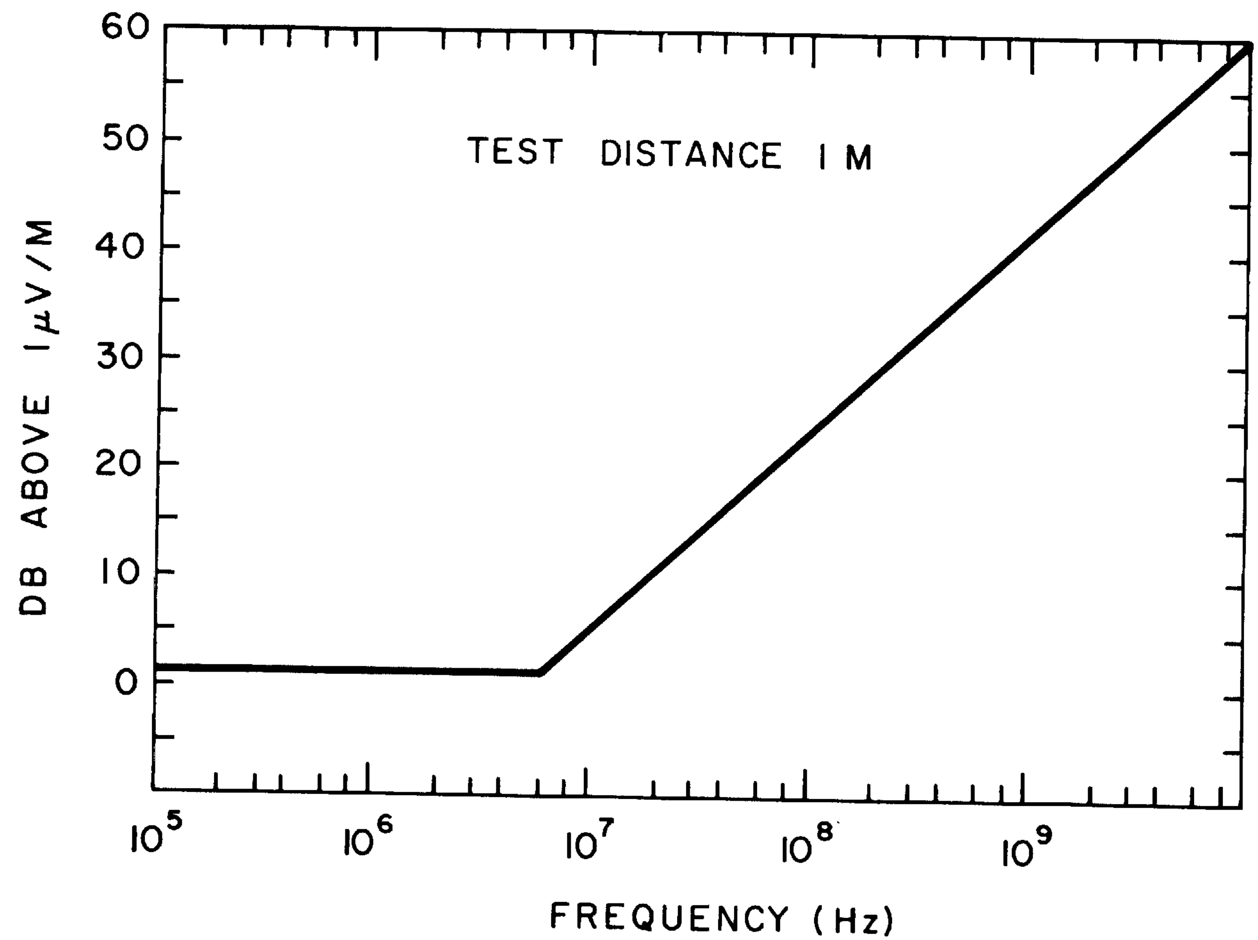


Fig 3.14

LIMITS FOR RADIATED EMISSION
ELECTRIC FIELD

APPENDIX C

Screening of Electronic Parts for Flight Equipment

This appendix to the PPL is intended to provide nominal levels of screening which may be used to upgrade conventional MIL parts for flight applications when Established Reliability (ER), TX, or other high reliability parts are not available. The GSFC specifications referenced in the PPL include screening. Reference is made to the Preface for a brief explanation of ER and TX parts specifications.

It is important to emphasize that the screening tests suggested here are nominal in the sense that many have been drawn from existing MIL and NASA part specifications. They are considered a baseline level on which more protective, and selective screens can be built depending on the program needs, capability, reliability objectives and mission requirements.

The screening tests are tabulated in a general outline format to permit project personnel to estimate screening costs and scheduling. Detail test procedures and criteria may be derived from referenced documents or by contacting the Applications Section. There are many other screening techniques in use which may be suitable, such as those contained in GSFC Specifications S-450-P-3A and S-450-P-4A developed for the NIMBUS Program.

Table 01.—Screening Outline for Capacitors[1]/

Category \ Test Sequence	1 Initial Measurements 2/	2 Temperature Cycling	3 Seal Leak Tests	4 Voltage Conditioning	5 Final Measurements and Tests	Reference Documents
a) Ceramic, Gen. Purpose	D.W.V.; I.R.; Cap; D.F.	-55 to 85°C per MIL-STD-202 Method 102, Cond. D	----	2 x rated voltage at rated elevated Temp. (but ≤ 125°C) for 100 hours	Repeat initial measurements	MIL-C-39014; GSFC S-450-P-4A
b) Ceramic, T.C.; Porcelain	D.W.V.; I.R.; Cap; D.F. or Q	-55° to 85 C per MIL-STD-202, Method 102, Cond. D	----	1.5 x rated voltage at rated elevated Temp. (but 125 C) for 100 hours	Repeat initial measurements	GSFC S-450-P-4A; MIL-C-20; MIL-C-11272
c) Glass	D.W.V.; I.R.; Cap; D.F. or Q	----	----	3 x rated voltage at 25 C for 50 hours	Repeat initial measurements	GSFC S-450-P-4A; MIL-C-23269
d) Tantalum (Wet Slug)	D. C. leakage; Cap; D.F. or P.F.	-55° to 85 C per MIL-STD-202, Method 102, Cond. D. Measure dc leakage immediately after final cycle.	1) Hermetic-sealed: Fine and gross leak tests 2) Elastomer-sealed: Acid indicator test	Rated voltage at 85°C for 168 hours	Repeat initial measurements on all units. Perform acid indicator test on elastomer-sealed units, only.	MIL-C-39006; GSFC S-450-P-4A
Tantalum 3/ (solid)	D.C. leakage; Cap; D.R. or P.F.	-55 to 85 per MIL-STD-202, Method 102, Cond. D	----	Rated voltage at 85 C for 168 hours	Repeat initial measurements	MIL-C-39003
e) Film (paper or plastic)	D.W.V.; I.R.; Cap; D.F.	-55 to 85 C per MIL-STD-202 Method 102, Cond.D	"CP" and "CH" styles, only: Gross leak test	1.4 x rated voltage at 85°C for 100 hours	Repeat initial measurements	GSFC S-450-P-4A; MIL-C-25; MIL-C-27287 MIL-C-18312
f) Mica	D.W.V.; I.R.; Cap D.F. or Q	----	----	1) Wire lead units: 2 x rated voltage at 125°C for 48 hours 2) Button: 1.5 x rated voltage at 25°C for 100 hours	Repeat initial measurements	GSFC-S-450-P-4A; MIL-C-5 MIL-C-10950
g) Variable, Glass	D.W.V.; I.R.; Cap; Q, Torque	3 cycles: -55° to 125°C	----	----	Repeat initial measurements. Perform visual inspection	GSFC S-450-P-4A; MIL-C-14409

Notes: 1/ Test procedures and requirements are in accordance with those in the applicable Military or NASA procurement document. For additional information, and to establish rejection criteria, see the reference documents or consult the Applications Section.
2/ Legend: D.W.V. = Dielectric Withstanding Voltage; I.R. = Insulation Resistance; D.F. = Dissipation Factor; P.F. = Power Factor.
3/ Recommended screening for non-standard, "non-E.R." solid tantalum capacitors.

TABLE 04. SCREENING OUTLINE FOR SUBMINIATURE FUSES

Test Sequence / Category	1	2	3	4	Reference Documents
	Initial Measurements	Temperature Cycle	Burn-in	Final Measurements	
Fuses, Subminiature	Visual and Mechanical Inspection, Resistance Voltage Drop @ 75% rated current	MIL-STD-202, Method 102, Cond. C	75% of rated current for 168 hours.	Visual, Voltage Drop @ 75% rated current.	

TABLE 05. SCREENING OUTLINE FOR INDUCTORS 1/

Test Sequence / Category	1	2	3	4	5	Reference Documents
	Initial Measurements 2/	Thermal Shock	Temperature Cycle	Seal Leak Test	Final Measurements and Tests	
a) Coils, fixed molded, RF	D.C. Resistance, IR, DWV, Inductance, Q, Self Resonant Freq.	----	MIL-STD-202 Method 102A, Cond. D	----	Repeat initial measurements and visual	MIL-C-39010 GSFC-S-450-P-4A
b) Transformers, Miniature Audio	DWV, Induced Voltage, IR, DC Resistance of PRI and SEC, Resistance Unbalance (where applicable), Inductance, Inductance Unbalance (where applicable), Polarity.	MIL-STD-202 Method 107B Cond. A.	----	MIL-T-27 Para. 3.7 (Gross leak test)	Repeat initial measurements and visual	MIL-T-39013 GSFC-S-450-P-4A

1/ Test procedures and requirements are in accordance with those in the applicable Military or NASA Procurement Document. For additional information, and to establish rejection criteria, see the referenced documents or consult the Applications Section.

2/ Legend: DWV —Dielectric Withstanding Voltage; IR—Insulation resistance.

TABLE 06. GENERAL SCREENING OUTLINE FOR RELAYS 1/

Test Sequence / Category	1	2	3	4	5	6	7	8	Reference Document 2/
	Seal Leak Test	Initial Meas-ments	Vibration	High Temp Soak	Low Temp Miss Test	Room Temp Miss Test	Seal Leak Test	Final Meas-ments	
Relays-Latching and Non-Latching	Para. 4.5.1 Fine leak radio active tracer or mass Spec-trometer Para. 4.5.2 Gross leak test	Para. 4.6 Coil Resis-tance Pull in and Drop out Voltage Contact Re-sistance Contact transfer Charac-teristics Insulation Resistance Dielectric Strength	Para. 4.7 100-2000 Hz 30g peak	Para. 4.9 16 hrs at 125°C	Para. 4.11 1000 opera-tion miss test at -65°C	Para. 4.12 5000 opera-tion miss test at 25°C	Para. 4.5.1 and 4.5.2 Repeat test sequence no. 1	Para. 4.6 Repeat test sequence no. 2	GSFC-S-311-P2

1/ For additional information, and to establish rejection criteria, see the referenced documents or consult the Applications Section.
2/ Other screening tests in this specification are provided for special applications.

TABLE 07. SCREENING OUTLINE FOR RESISTORS 1/

Test Sequence / Category	1 Initial Measurements	2 Bake	3 Temperature Cycle	4 Seal Leak Test	5 Burn-in	6 Final Measurements and Tests	Reference Document
a) Resistors, Fixed Carbon Comp.	--	48 hrs at 100°C	MIL-STD-202 Method 102A Cond. D	--	--	Resistance and Visual	GSFC-S-450-P-4A
	The necessity for screening and the type of screening for a carbon composition resistor is governed by the type of construction, manufacturer, application stability requirement and the storage history.						
b) Resistors, Fixed Film, General Purpose	Resistance	–	MIL-STD-202 Method 102A Cond. D	--	1.5 x rated pwr for 24 hrs. at Room Temp.	Resistance and Visual	MIL-R-39017 Group A Insp. Subgroup 1
c) Resistors, Fixed Film, High Stability	Resistance	--	MIL-STD-202 Method 102A Cond. C	Immerse 2/ in Dye Liq, Vacuum 30 min.; Pressure 30 min.	5 x rated pwr (1/20, 1/10, and 1/8 w) 4 x rated pwr (1/4 w) 2-1/4 rated pwr (1/2 and 3/4 w) for 1 hr. at Room Temp.	Resistance and Visual	MIL-R-55182 Group A Insp. Subgroup 1A
d) Resistors, Fixed Wirewound, Accurate	Resistance	--	MIL-STD-202 Method 102A Cond. C	--	1.0 x rated pwr for 100 hrs. at 125°C	Resistance and Visual	MIL-R-39005 Group A Insp. Subgroup 1
e) Resistors, Fixed Wirewound, Power Chassis Mount Resistors, Fixed Wirewound, Accurate Power	Resistance	--	MIL-STD-202 Method 102A Cond. C	--	1.0 x rated pwr for 100 hrs. at 25°C	Resistance and Visual	MIL-R-39007/ MIL-R-39009 Group A Insp. -- Subgroup 1
f) Resistors, Variable, Low Power Trimmers	Resistance	24 hrs at 150°C	MIL-STD-202 Method 102A Cond. C	--	1.0 x rated pwr for 1-1/2 hr on 1/2 hr off for 96 hrs. at 25°C	Resistance, Peak Noise, and Visual	MIL-R-39015 Group A Insp. Subgroup 1
g) Resistors, Variable, Wirewound, Power	Resistance	24 hrs at 150°C	MIL-STD-202 Method 102A Cond. C	--	1.0 x rated pwr for 1-1/2 hrs on 1/2 hr off for 96 hrs at 25°C	Resistance, Peak Noise, and Visual	

1/ Test procedures and requirements are in accordance with those in the applicable Military or NASA procurement document. For additional information, and to establish rejection criteria, see the referenced documents or consult the Applications Section.

2/ This test is only for hermetically sealed parts.

TABLE 08. SCREENING OUTLINE FOR DIODES 1/

Category \ Test Sequence	1 High 2/ Temperature Storage	2 Thermal Shock	3 Seal Leak Test	4 Pre Burn-in Test	5 Burn-in Test	6 Post Burn-in Test	Reference Document
a) Diodes, General Purpose	200°C for 48 hours	MIL-STD-750 Method 1051 Test Condition C except 10 cycles total, 15 min. rest at each temperature extreme	Fine Leak: MIL-STD-202 Method 112 Test Condition C and Gross Leak	Measure I_R and V_F at 25°C	168 hours at 100°C at specific values of V_R and I_O	Repeat pre burn-in Test No. 4	See: MIL-S-19500/118C MIL-S-19500/240B
b) Diodes, Rectifier, Silicon	200°C for 48 hours	Same	Same	Same	168 hours at 100°C at specific values of V_R and I_O	Same	MIL-S-19500/155C
c) Diodes, Reference, Silicon, 5% Tolerance	175°C for 48 hours	Same except high temperature is 175°C	Same	Measure BV, I_R and Z at 25°C	168 hours at 100°C at specified I_Z	Same	MIL-S-19500/115 MIL-S-19500/117 MIL-S-19500/124
d) Diodes, Switching	200°C for 48 hours	Same as Diodes, General Purpose a)2	Same	Measure I_R and V_F at 25°C	168 hours at 100°C at specific values of V_R and I_O	Same	MIL-S-19500/116 MIL-S-19500/144 MIL-S-19500/169D MIL-S-19500/231B
e) Diodes, Variable Capacitance	150°C for 48 hours	Same as a)2	Same	Measure I_R @ max WV I_F @ specified V_F C @ specified V_R	168 hours at 100°C at specified max continuous working voltage (V_R)	Same	MIL-S-19500/329

1/ Test procedures and requirements are in accordance with those in the applicable Military or NASA procurement document. For additional information, and to establish rejection criteria, see the referenced documents or consult the Applications Section.

2/ **All high temperature testing must be performed in an inert atmosphere to avoid tarnishing of leads. The user should assure himself that high temperatures will not tarnish leads.**

TABLE 09. SCREENING OUTLINE FOR TRANSISTORS 1/

Test Sequence / Category	1 High 2/ Temperature Storage	2 Thermal Shock	3 Reverse Bias Burn-in	4 Acceleration	5 Seal Leak Test	6 Pre Burn-in Test	7 Burn-in Test	8 Post 3/ Burn-in Test	Reference Document
a) Transistors; Germanium	Not recomended for Flight Use (See Appendix A)								
b) Transistors, NPN, Silicon, Low Power and Switching	200°C for 24 hours	MIL-STD-750 Method 1051, Test Cond. C. except 10 cycles total. 15 min. rest at each temp. extreme	None	MIL-STD-750 method 2006, except 20,000 g's Y, orientation, one time only	MIL-STD-202 Method 112, Test Cond. C, and gross leak	Measure I_{CBO} or I_{CES} and h_{FE} at specified values of V_{CB}, V_{CE} and I_C	168 hours at 25 C at specified V_{CB} and P_T	Repeat the Pre-Burn-in Test No. 6 $\Delta h_{FE} = \pm 15\%$ $\Delta I_{CBO} = 100\%$ or 5 nA*	MIL-S-19500/181C, 225 C/251E/312B
c) Transistors, PNP, Silicon, Low Power and Switching	Same	Same	12 hours at 175°C with V_{CB} and I_E specified	Same	Same	Measure I_{CBO} and and h_{FE} at specified V_{CB}, V_{CE} and I_C	Same	Same	MIL-S-19500/290B 291B, 323
d) Transistors, NPN, Silicon, High Power	Same	Same	None	None	Same	Measure I_{CES}, h_{FE} and I_{EBO} at specified V_{CE}, V_{EB} and I_C	168 hours at 100 C at specified V_{CE} and P_C	Same Except, $\Delta I_{EBO} = 100\%$ or 100 A*	MIL-S-19500/262E
e) Transistors, Dual Matched Pair NPN or PNP Silicon Transistors	Test same as NPN or PNP silicon low power and switching transistors, each transistor of matched pair is tested separately, but simultaneously in time.								MIL-S-19500/270B MIL-S-19500/355
f) Transistor, Unijunction	200°C for 24 hours	Same	None	Same	Same	Measure , I_{EB_2O} and R_{BB} at specified V_{B_2E}, I_{B_1}, $V_{B_2B_1}$ & I_E	168 hours at 125 C at specified V_{BB} and I_E	Repeat No. 6 $\Delta R_{BBO} = \pm 20\%$ $\Delta \eta = \pm 5\%$ $\Delta I_{EB_2O} = 100\%$ or 50 nA*	MIL-S-19500/75B
g) Transistor, Field Effect	200°C for 24 hours	Same	None	Same	Same	Measure I_{GSS}, I_{DSS} and $\|y_{fs}\|$ at specified V_{GS} and V_{DS}	168 hours at 125 C at specified V_{GS} and V_{DS}	Repeat No.6 $\Delta I_{DSS} = \pm 10\%$ $\Delta \|y_{fs}\| = \pm 20\%$ $\Delta I_{GSS} = 100\%$ or 5nA*	MIL-S-19500/378

1/ Test procedures and requirements are in accordance with those in the applicable military or NASA procurement document. For additional information, and to establish rejection criteria, see the referenced documents or consult the Applications Section.

2/ All high temperature testing must be performed in an inert atmosphere to avoid tarnishing of leads if tinned leads are used. The user should assure himself that high temperatures will not tarnish leads.

3/ The listed maximum acceptable delta (Δ) changes in the electrical parameters are guideline values only. The proper delta (Δ) change criteria for device rejection must be determined individually by the user.

- Whichever is greater.

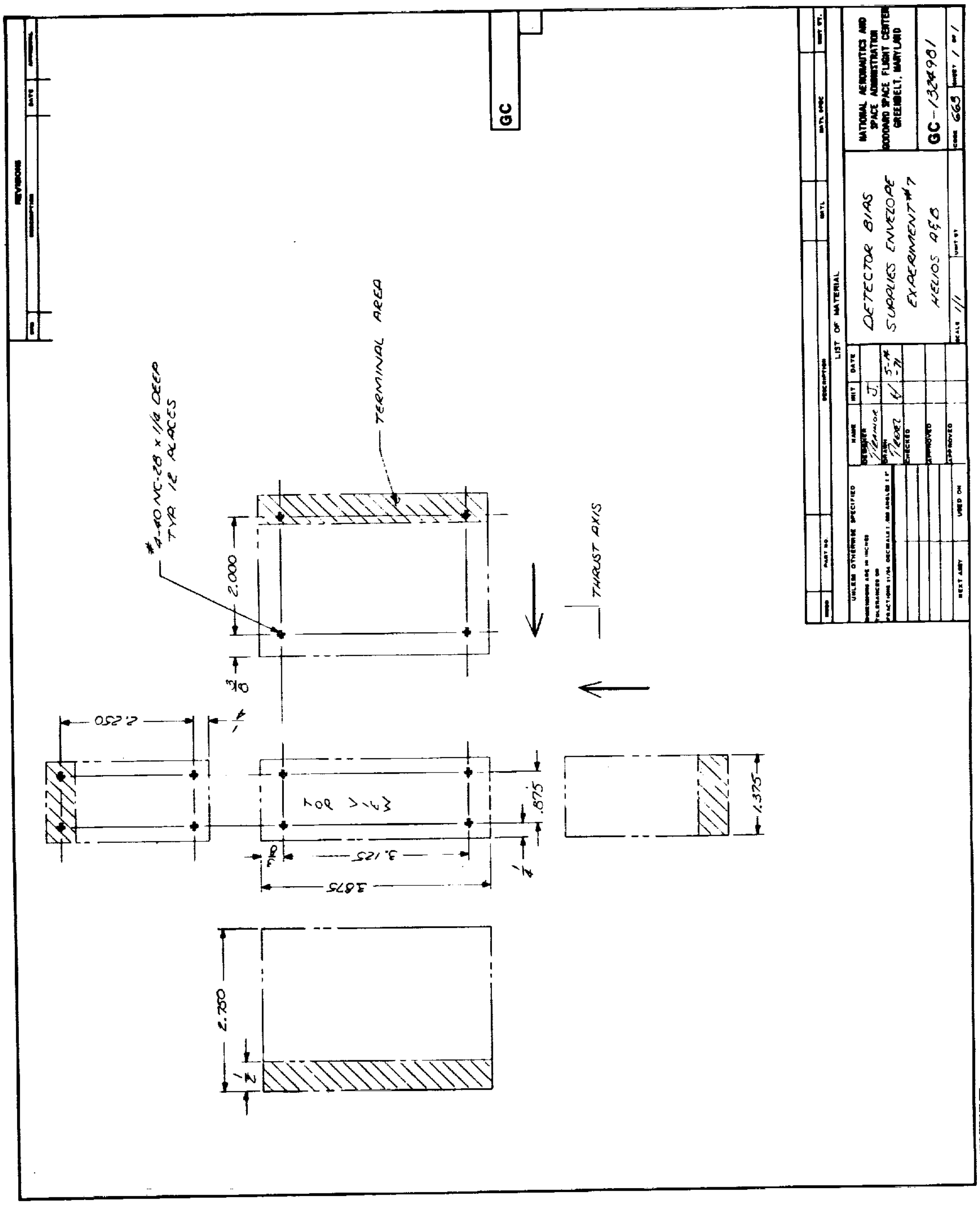
TABLE 10. SCREENING OUTLINE FOR MICROCIRCUITS

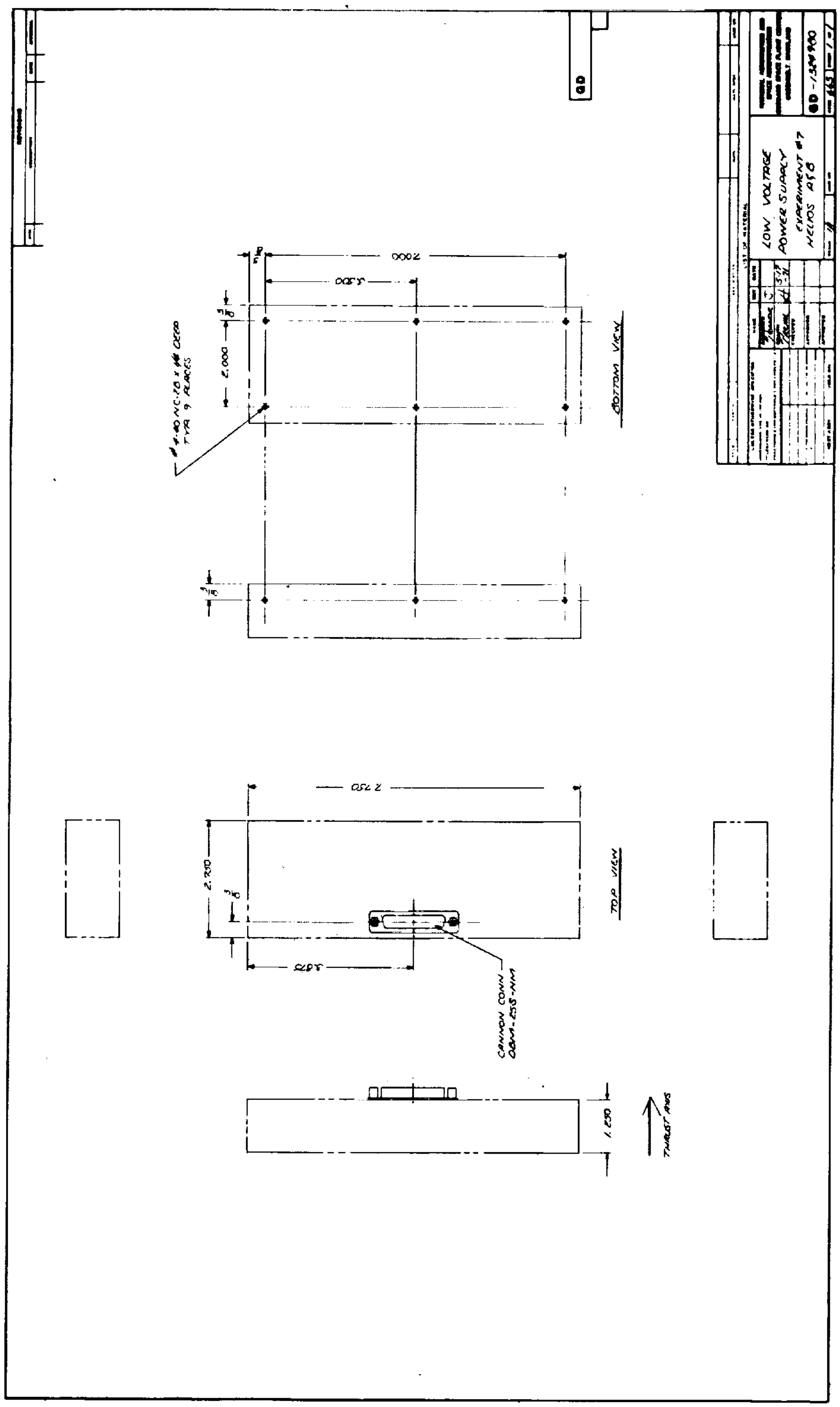
Test Sequence / Category	1 High Temperature Storage	2 Thermal Shock	3 Mechanical Shock	4 Acceleration	5 Radiographic	6 Seal Leak Test	7 Burn-in	Reference Document
Microcircuits	Screen in accordance with MIL-STD-883, Method 5004, Class A. Pre-cap inspections shall be performed by the manufacturer. Lot qualification (Para. 3.1.14 of 5004) may be waived, depending upon the particular procurement and application.							

TABLE 14. SCREENING OUTLINE FOR THERMISTORS 1/

Test Sequence / Category	1 Initial Measurements	2 Bake	3 Temperature Cycle	4 Seal Leak Test	5 Burn-in	6 Final Measurements and Tests	Reference Document
a) Thermistors, (Thermally Sensitive Resistor) (Negative Temp. Coef.)	Zero-Power Resistance at 25°C and IR	24 hrs at 125°C	MIL-STD-202 Method 102A Cond. C	--	--	Zero-Power Resistance at 25°C and Visual	GSFC-S-450-P-4A
b) Thermistors, Fixed Silicon (Positive Temp. Coef.)	Zero-Power Resistance at 25°C	--	MIL-STD-202 Method 102A Cond. C	--	1.5 x rated pwr. for 96 hrs at 25°C	Zero-Power Resistance at 25°C and Visual	GSFC-S-450-P-4A

1/ Test procedures and requirements are in accordance with those in the applicable Military or NASA procurement document. For additional information, and to establish rejection criteria, see the referenced documents or consult the Applications Section.


TERMINAL AREA
THRUST AXIS
2.000
2.250
3.125
3.875
.875
1.375
2.750
LIST OF MATERIAL
REVISIONS
DETECTOR BIAS
SUPPLIES ENVELOPE
EXPERIMENT #7
HELIOS A&B
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND
GC-1324901
GC


LOW VOLTAGE
POWER SUPPLY
EXPERIMENT #7
HELIOS A&B
GD-1324900
LIST OF MATERIAL
BOTTOM VIEW
TOP VIEW
2.000
1.500
2.000
2.750
2.350
1.375
1.250
#4-40 NC-2B x 1/4 DEEP TYP 9 PLACES
CANNON CONN DAM-25S-NM
THRUST AXIS
GD

APPENDIX 3

SPECIFICATIONS FOR PHOTOMULTIPLIER TUBE

SPECIFICATIONS FOR
PHOTOMULTIPLIER TUBE
POWER CONVERTER PS-20

March 6, 1969

1.0 General

These specifications are intended to cover a general purpose high-voltage, high frequency DC to DC converter for use with photomultipliers in scintillation detectors for spacecraft pulse height analysis applications. A complete system will consist of from one to four multiplier stacks for single photomultiplier tubes and a main converter with a capability of driving as many as four multipliers. The number of multipliers shall be selectable after delivery.

1.1 Applicable Documents

1.1.1 GSFC X-325-67-70, "Magnetic Field Restraints for S/C Systems and Subsystems."

1.1.2 GSFC S-320-S-1 "General Environmental Test Specifications for Spacecraft and Components using Launch Environments Dictated by Scout FW-4 and Scout X-258 Launch Vehicles," May 20, 1966.

1.1.3 NPC 200-3: NASA Inspection System Provisions for Suppliers of Space Materials, Parts, Components and Services.

1.1.4 NGB 5300.4 (3A): NASA Quality Requirements for Hand Soldering of Electrical Connections.

1.1.5 MSFC-STD-271: NASA, Marshall Space Flight Center, Standards for Fabrication of Welded Electronic Modules.

1.1.6 Where differences exist between the requirements of this specification and the documents listed above, the requirements of this specification shall apply.

2.0 Operating Characteristics

2.1 Input

2.1.1 Voltage: The source operating limit is 10.7 Vdc +10% -15%.

2.1.2 Grounding: The negative power input line will be at circuit common potential but isolated from the output circuit common by more than 100K resistive impedance and less than 100 picofarads capacitance.

2.1.3 Input Power: The input power at no load and any operating input voltage shall not exceed 100 milliwatts and may increase to no more than 150 milliwatts at full load.

2.1.4 Source Impedance: The dc internal impedance of the source power will be less than 1.5 ohms and will increase to no more than 4.5 ohms up to one mHz.

2.1.5 Ripple Tolerance: The power supply shall be capable of operating within specifications when the power source contains electrical noise between power bus lines and common mode noise with respect to output circuit common. This electrical noise can have a maximum amplitude of 300 millivolts peak-to-peak and a bandwidth from 10 to 10^6 Hz.

2.1.6 Input Current Limiter: A current limiter shall be located on the input line to limit total input current to twice the normal full load value. The limiting action shall have no effect when operating at less than this value.

2.1.7 Noise Feedback: The ac component of input current feeding back to the power source shall be less than 0.5 milliamperes peak-to-peak. Paragraph 2.1.4 is applicable when measuring this current.

2.1.8 <u>Overvoltage Protection</u>: The converter shall not be damaged and the functional performance shall not be permanently impaired or degraded if the applied voltage polarity is reversed or if there are input transients of any peak amplitude up to 16 volts for a duration of ten milliseconds or less. The converter shall not be damaged and its functional characteristics not impaired by application of any supply voltage from 0 to 12.3 volts dc indefinitely, nor shall the output voltages exceed 20% of the nominal value. Components must be rated for this extreme. Current limiting per paragraph 2.1.6 is also applicable.

2.1.9 <u>Temperature Limits</u>: Normal temperature operating limits will be between -20°C and +40°C.

2.2 Operation

2.2.1 <u>Starting Time</u>: The converter shall start at full load in less than five seconds after being off for a period of at least two hours and at any operating temperature or input voltage. The output voltage shall stabilize to $\pm$ 0.25% of that value within one minute after turn-on.

2.3 Output

2.3.1 A twelve stage multiplier shall provide tapped outputs to operate an RCA C7151Q photomultiplier tube. The voltage distribution is as follows: Equal voltage between all dynodes and last dynode and anode and twice that value between photocathode and first dynode.

2.3.2 A fourteen stage multiplier shall provide tapped output to operate an EMI 9712 photomultiplier tube. The voltage distribution is as follows: Equal voltage between all dynodes and last dynode and anode and three times that value between photocathode and first dynode.

2.3.3 The converter shall be designed so the dynode voltage increment can be set independently for each multiplier at any value from 110 to 150 volts in increments of five volts, measured from any dynode to an adjacent dynode. In addition, the converter output shall be adjustable by resistor or zener diode selection over a range of ±10%. The converter shall not be damaged if the voltage adjust network is left open or shorted.

2.3.4 Grounding: The secondary circuit common point must be selectable from any one of the dynode, anode or photocathode leads on individual multipliers driven from a common converter.

2.3.5 Load Regulation: All output voltages shall be regulated within ±0.25% for single anode currents up to six microamperes each between 9.6 and 12.3 input volts and for all operating temperatures.

2.3.6 Overload Protection: The anode supply shall current limit with the threshold occurring between 6.0 and 8.0 microamperes on each tube. The individual dynodes shall current limit at 0.5 ± 0.25 of the limiting value of the preceding stage at least down to the eighth dynode, and no less than 0.1 microampere at any dynode below the eighth. The unit must be so designed that a direct short on any output lead from the central converter or any multiplier output shall not result in permanent damage.

2.3.7 Ripple: Under all photomultiplier tube load and input conditions up to the current prescribed in paragraph 2.3.4, all dynode and anode output lines shall have a ripple or noise amplitude less than one millivolt peak-to-peak measured from any dynode output or anode output to circuit common.

3.0 Mechanical

3.1 General: The converter and multipliers may be designed using printed circuits, welded wire, welded modules, point to point, solder or any combination of techniques. However, mechanically moving parts or potentiometers may not be employed.

3.2 Solder Terminals: All connections between external terminals and internal printed circuits shall be accomplished by means of insulated wire at least one-half inch long. This is intended to prevent overheating the printed circuit pad when external connections are made to the terminals. The output terminals may be arranged in any convenient order. See Figure 2.

3.3 Connectors: Connector types are called out in Figures 1 & 2. In no case must the center conductor be at more than $\pm$ 160 volts peak from output circuit common. The shield shall be at output circuit common potential. Connectors may not be mounted on the top or bottom surface of the converter.

3.4 Cables: Interconnecting cables shall be a coaxial type with suitable right angle connector compatible with paragraph 3.3. The contractor will recommend a cable type which will meet the radiation requirements of MIL-I-26600. The output characteristics of the supply shall be independent of the cable length for lengths eighteen inches and less. Multipliers will be supplied with two cables each: connector-to-connector, 18" long, and connector-to-blank, 18" long.

3.5 Size: Refer to Figures 1 & 2.

3.6 Weight Schedule:

Converter	120 grams maximum
Multiplier (each type)	70 grams maximum (each)

3.7 Encapsulation: The main converter and multipliers shall be conformally coated in polyester base epoxy or polyurethane as approved by the technical representative.

4.0 Environmental Perturbation:

4.1 Materials: Non-magnetic materials should be used wherever possible and construction should be in accordance with magnetic field restraints as specified in references 1.1.1 and 1.1.2, and summarized as follows:

4.1.1 After a 15 gauss exposure each assembly (one converter and four multipliers) must have a residual magnetism of less than 32 gamma at eighteen inches.

4.1.2 After a 50 gauss deperm each assembly must have a residual magnetism of less than two gamma at eighteen inches.

4.1.3 Each assembly must have a stray magnetism of less than two gamma at eighteen inches.

4.2 RF Radiation: The converter and multipliers shall be enclosed in shielded containers electrically connected to the output circuit common such that the external electric field is less than one microvolt per meter at a distance of ten inches from any multiplier or the converter when measured with an rms reading field strength meter. The stray ac magnetic field measured at one meter shall be less than 10^{-4} gammas.

4.3 Harmonic Content: The voltage multiplier driving voltage must contain not more than 10% harmonic distortion from a true sine wave to minimize harmonic radiation.

4.4 GSFC will provide for testing of requirements set forth in paragraphs 4.1 and 4.2.

5.0 Environmental Testing: The converter shall be capable of passing the SAS-B environmental specifications in accordance with the documents listed in paragraph 1.1. The levels for the environmental design qualification test applicable to this converter are as follows:

5.1 Storage temperature: (non-operative)

-50°C	6 hours
+75°C	6 hours

5.2 Humidity: 95% relative humidity at 40°C for 50 hours.

5.3 Acceleration: (operative) 28 g for three minutes in three mutually perpendicular directions.

5.4 Vibration: (operative) Each vibration is done once in each of three mutually perpendicular directions.

5.4.1 Sinusoidal:

Frequency (Hz)	Level
10-24	0.4 inches (double ampl.)
24-30	±12.0 g
30-80	±20.0 g
80-110	±37.0 g
110-2000	±12.0 g

5.4.2 Random Vibration (4 min/axis):

Frequency Band (Hz)	APSD level (g^2/Hz)
20-43	0.07
43-56	0.20
56-70	0.40
70-100	1.50
100-150	.60
150-200	.20
200-2000	.07

OA: 14.9 g rms

5.5 Shock: (operative) 40 g, 1/2 sine wave, 6 milliseconds, each of three mutually perpendicular directions.

5.6 Thermal Vacuum: (operative) Pressure equal to 10^{-5} mm Hg or less. Temperature of case 50°C for 24 hours and -10°C for 24 hours.

5.7 Corona Discharge

The contractor shall perform the corona discharge test as follows: Pressure in the range 10^{-3} to one mm Hg, all high voltage points encapsulated with RTV-60. Connect 0.01 uf capacitor between one anode and oscilloscope. The pressure shall be held between 100 and 200 microns Hg for at least two hours. No transients having amplitudes greater than 2 millivolts shall occur at the anode connection during this entire test.

6.0 Quality Assurance and Reliability:

High reliability of the system shall be assured by choice of good design, inspection and testing. A suitable reliability and quality assurance program shall be in effect. Demonstrated compliance with the provisions of NASA Quality Assurance Specifications NPC-200-3 and NHB5300.4(3A) is required. As a design goal the power supply shall have a 95% probability of operating in a space environment without failure for 10,000 hours, with the calculation based on individual component and connection reliability.

6.1 Design: The system design shall be as simple as possible to assure high reliability. Provisions shall be made to allow for component or element value drift. The components or elements shall be derated to reduce the chance of parts failure due to overvoltage or excessive power dissipation. The use of germanium semiconductors must be cleared with the technical representative.

6.2 Inspection: Inspection standards shall be established at the component, module or board, and systems levels to detect fabrication errors, contamination, poor workmanship, etc. Inspection shall be on a 100% basis.

6.3 Electrical Testing: An adequate testing program shall be established to ensure compliance with the provisions of this specification. All critical components, including all semiconductors and tantalum capacitors, are to be given accelerated aging tests. The pertinent component parameters are to be measured and recorded before and after the accelerated aging test and comparisions made to determine whether the parameter values drift abnormally. The aging is to consist of powered storage for at least five days. Powered storage is defined as follows:

Tantalum Capacitors: Stored at 85°C with manufacturer's voltage rating impressed.

6.3.1 Semiconductor Screening: Only hi-rel parts will be used in the SAS spacecraft. The GSFC Preferred Parts List specifies certain requirements for parts procurement and screening. In addition to those, the SAS Project has specific requirements for semiconductor screening that apply to all diodes, transistors, and integrated circuits. Specifically, 100% of all semiconductor devices used in prototype or flight hardware must undergo the following test sequence:

a) Visual inspection before sealing with a minimum magnification of 40.

b) Temperature cycling from -65°C. to maximum rated storage temperature.

c) Centrifuge

d) Electrical Test

STATEMENT OF WORK

The proposal resulting from this RFP and the contract shall be based on:

a. Design of a power supply system meeting the requirements of the attached specifications, Photomultiplier Tube Power Converter PS-20

b. Development of plans for inspection and testing to meet all specification requirements.

c. Delivery shall be made on each of the following items:

1 each engr. model system consisting of

1 each PS 20C converter
4 each PS 20M12 multipliers
2 each PS-20M14 multipliers

3 each flight system consisting of

6 each PS 20C converters
12 each PS 20M12 multipliers
4 each PS 20M14 multipliers

d. Delivery of the engr. model shall be made 90 days after receipt of contract.

e. Acceptance of the engr. model by the purchaser shall precede start of construction of the flight units.

f. Delivery of the flight units shall follow 90 days after acceptance of the prototype by the purchaser. A minimum of ten days will be required for the prototype acceptance testing.

g. Preliminary drawings shall be delivered with the prototype assembly and reproducibles as stipulated in the specifications shall be delivered with the flight systems.

e) 336 hours $\pm$ 36 hour burn-in at 100°C. at 80% of part rated power.

f) Electrical Test

g) Fine and gross leak tests

h) Final inspection including X-ray, if possible.

6.4 Testing of Power Supply: Each system shall be tested under all conditions of input voltage from 9.6 to 12.3 volts, output load from zero current to short circuit at anode, and temperature from -40°C to 50°C at atmospheric pressure. Performance curves shall be plotted as follows: Anode and all dynode voltages shall be plotted as a function of load. Separate graphs shall be plotted for input voltages of 9.6, 10.7 and 12.3 and temperatures of -40°C, -10°C, 25°C and 50°C. The load shall consist of an RCA type 6199, or EMI 9530 photomultiplier tube as appropriate, with a variable (non-pulsing) light source. The light intensity shall be varied to produce the desired anode current. These graphs, and all the data from the testing of the individual components and the assembly shall be delivered to GSFC at the same time as delivery of each converter.

7.0 Documentation:

In addition to the test data specified above, the contractor shall provide a complete set of specifications, complete reproducible circuit schematics including assembly prints showing artwork, a parts list identifying manufacturer and type for all parts, and a circuit description at the time of delivery of the first system.

8.0 Marking:

Each module shall be unambiguously marked: The marking shall be as follows:

Converter:	PS 20 C - (Serial Number)
Multiplier:	PS 20 M12 - (Serial Number)
	PS 20 M14 - (Serial Number)

Serial numbers shall begin with one for each type module (converter and multiplier) and run consecutively.

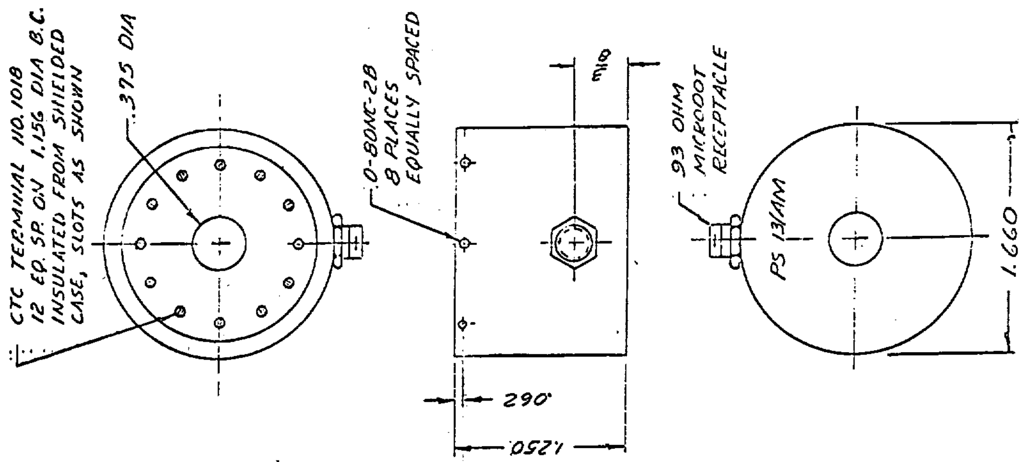


FIGURE 2

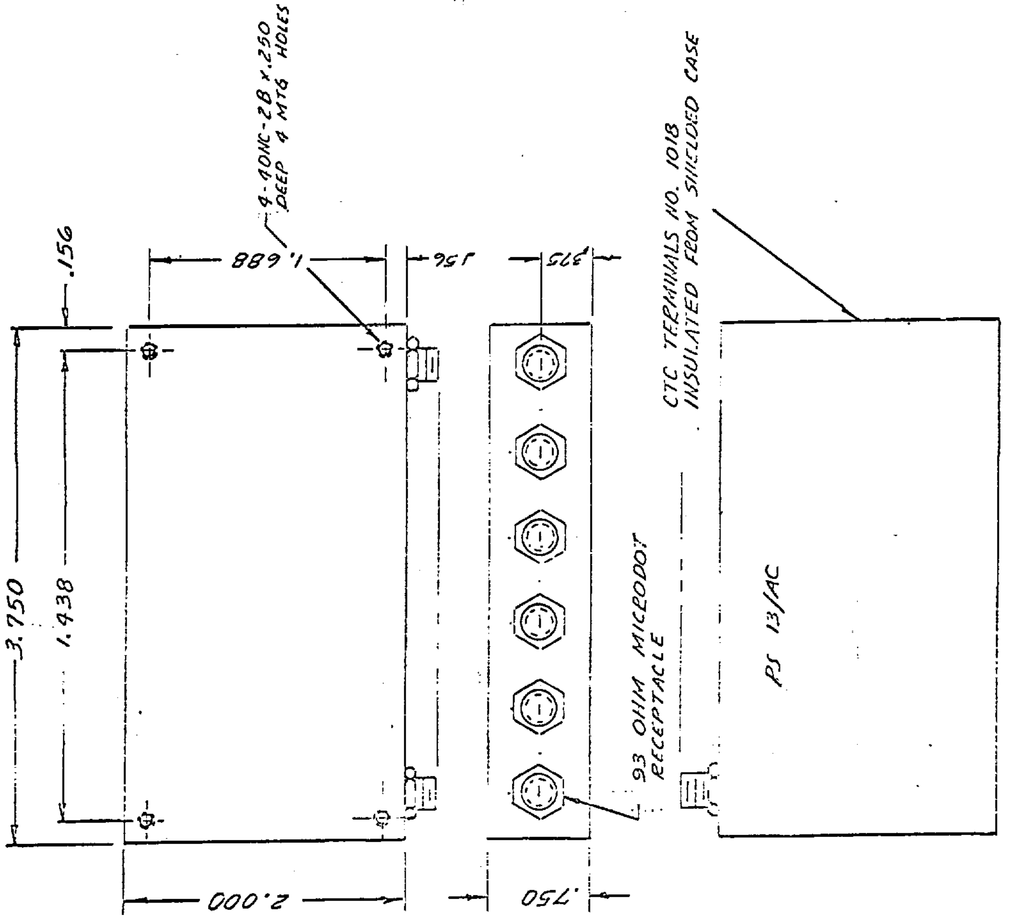


FIGURE 1